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ICEBREAKER DESIGN SYNTHESIS
PHASE 2
ANALYSIS OF CONTEMPORARY ICEBREAKER PERFORMANCE

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The contents of this report reflect the views of the contractor and not necessarily the official views or policies of Transport Canada

Un sommaire en français de ce rapport est inclus avant la Table des matières.

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16. Abstract

This project studied the icebreaking technology of fourteen ship designs, primarily used for ice escort. The vessels have features which both complement and extend the features studied in Phase 1.

Eleven captains were interviewed to determine how their ships' design features affect performance and the ability to perform their assigned mission roles.

The full scale data for the ships were analysed, and comparison made between the performances of the ships in both phases. The influence of icebreaker design features and parameters, and hull and environmental conditions upon performance in different performance categories was determined.

Performance estimation models for level ice, ridges, turning, and open water resistance were developed, extending the range of the models from phase 1.

The information and models give the ship designer and operator practical information on how ship design features affect the performance and ability to perform missions.

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16. Résumé

Les chercheurs ont analysé les performances de 14 brise-glace utilisés principalement comme escorteurs et pourvus de caractéristiques améliorées ou nouvelles par rapport à celles qui avaient été analysées au cours de la phase précédente de la recherche.

Les commandants de onze de ces navires ont été interviewés dans le but d'approfondir l'influence des caractéristiques de conception de leur navire sur ses performances et son aptitude à remplir les missions pour lesquelles il a été conçu.

Les résultats des essais en vraie grandeur menés au cours des deux phases de la recherche ont été analysés et un bilan comparatif des performances en a été tiré. L'influence des paramètres de conception et des caractéristiques conceptuelles sur les diverses catégories de performances a été également analysée, ainsi que celle de la forme géométrique de la coque et des conditions environnementales d'exploitation.

Les chercheurs ont élaboré des modèles de simulation permettant de prédire les aptitudes d'un brise-glace à progresser dans des glaces uniformes et à franchir les crêtes de pression, ainsi que ses qualités giratoires et sa résistance à la marche en eau libre, étendant la portée des modèles réalisés antérieurement.

Cette base de données ainsi que les modèles mathématiques constituent un outil prédictif utile, permettant aux architectes navals et aux armateurs de connaître à l'avance l'influence de tel ou tel paramètre de conception sur les performances d'un brise-glace et sur son aptitude à effectuer des missions précises.

17. Mots clés	18. Diffusion
Brise-glace, résistance à la marche, glaces uniformes, crêtes de pression, manoeuvrabilité, conception, performances, bilan comparatif.	Le Centre de développement des transports dispose d'un nombre limité d'exemplaires.

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SUMMARY

The influence of hull form, propulsion and steering system design features upon icebreaker operational performance in a wide range of environmental conditions has been determined from the analysis of dedicated full scale trials results and operator interviews for sixteen of the world's most important and modern icebreakers.

The work has resulted in the formulation of mathematical formulae or models whereby the icebreaking, manoeuvring and open water performance of icebreakers can be predicted at the design stage. Moreover, significant progress has been made towards understanding the important design links between individual measures of performance in idealized trials conditions and the overall measure of operational performance of icebreakers in carrying out their assigned missions.

In Icebreaker Design Synthesis Phase 1 (TP 9992E, Ref.91) the influence of design features and parameters upon the operational performance of six contemporary icebreakers, incorporating many innovative features, was analysed. These vessels were predominantly Canadian Beaufort Sea commercial icebreakers, designed to support Arctic offshore operations with the emphasis on the missions of ice management, towing, anchor handling and offshore supply. They had displacements up to 7000 tonnes, shaft powers up to 17 megawatts, hull forms incorporating short highly-flared bows, chines, reamers and bow wedges and propulsion systems with both open and ducted controllable pitch propellers. All had been tested in cold, strong, winter ice conditions and some in weaker spring/fall ice conditions.

This Phase 2 of Icebreaker Design Synthesis covered a larger number of worldwide vessels designed predominantly for the traditional icebreaker role of ice escort. The project included all significant ice class Canadian and US Coast Guard vessels, the cargo icebreaker M.V.Arctic, and the most recent Baltic and European designs. Ten vessel classes, which counting major refits amounted to twelve different designs, were included. Most vessels were of a more traditional design associated with operational requirements in both open water and in ice, having fully-formed hulls and longer, lower-flared bows. Propulsion systems included both open fixed pitch and open and ducted controllable pitch propellers. Two notable exceptions were of contemporary form. The Phase 2 group of vessels had displacements up to 40000 tonnes and shaft powers up to 45 megawatts. Different vessels had been tested in a wide range of environmental conditions from warm, deteriorating saline spring ice to cold, fresh winter ice.

The database from Phases 1 & 2, of dedicated ship trials performance information and performance assessments from operator interviews, covers virtually the complete spectrum of icebreaker size, power and design features, environmental conditions, hull conditions, individual performance categories and

operational missions undertaken by icebreakers. This database of measured full scale performance subsequently forms the most complete and reliable body of information to date for analysis.

The Phase 2 trials data were reduced to the same common non-dimensional format as developed in Phase 1 and then amalgamated with the Phase 1 data in a joint analysis for the influence of design and environmental parameters upon performance. The analysis covered the same performance categories as in Phase 1, namely, level ice resistance, propulsive performance, ridge performance, manoeuvring performance, broken channel performance, transit performance, propeller/ice interaction and open water performance. Mathematical models in the form of empirical formulae for predicting the performance of icebreakers with different combinations of design features and hull parameters and in different environmental conditions were then developed.

Operator interviews were also carried out with the Masters of the vessels in order to obtain qualitative information on performance in the wide range of operational situations not covered by dedicated trials, and to gain an understanding of the complex relationships between design features, different elements of ship performance in different ice regimes and overall performance in carrying out specific missions.

Consistent with the wide range of ship designs, environmental conditions, ship operations and missions covered by the study, the performance analysis provided a comprehensive quantitative and qualitative understanding of icebreaker performance.

The same influences of design features upon performance, identified in the small group of Phase 1 vessels (TP 9992E), were confirmed within the much larger combined group of vessels. The results however were far more reaching in scope, extending knowledge of icebreaker performance into the full range of design and environmental parameters, performance categories and missions conducted by the larger group of vessels.

The level ice performance analysis showed that correction of trials data for differences in environmental conditions could not be made satisfactorily, in the traditional manner, solely on the basis of ice flexural strength. Additional corrections for surface temperature, which influences frictional forces, and for ice salinity, which affects the total energy of the icebreaking process, were necessary. These corrections were made on the basis of the latest and ongoing research and resulted in a corrected data set which demonstrated logical and consistent influences of design parameters on performance. The method developed can be applied to any level ice trials data in order to compare ship performance on a common environmental basis.

Level ice resistance was found to be influenced signifi-

cantly by buttock and particularly flare angles at the bow; also strongly by ship beam and to a lesser extent by length and draft. Moreover, chined vessel resistance was not as sensitive to increasing ice thickness as for fully formed hulls.

Ridge performance analysis identified the first known influence of hull form on penetration energy, increasing bow flare angle providing a noticeable improvement in performance.

The high effectiveness of water lubrication on the ice in reducing level ice resistance, demonstrated in Phase 1, was confirmed. Additionally, high pressure air/water jets along the bow/ice interface provide significant resistance reduction.

The propulsive performance in level icebreaking ahead of all propulsion systems employed on icebreakers was determined. The results confirmed the significant advantage of ducted propulsion and demonstrated the operational flexibility of open controllable pitch propellers in maintaining relatively high performance at speeds far removed from the slow speed icebreaking design condition.

The turning performance of reamered vessels in ice has been shown to be highly predictable and dependent upon the local geometry of the waterline as defined by the width of the reamer divided by length of parallel side. A major step has also been made in understanding the turning ability of conventional non-reamered vessels, their performance being influenced strongly by both waterline shape, as defined in terms of the percentage length of parallel side, and the relative effectiveness of the steering system.

The open water resistance of contemporary icebreaker forms incorporating chines, reamers and wedges is shown to be significantly higher, to the order of 100% higher, than that of conventional fully formed vessels of the same size and form coefficients.

Analysis of the operator interviews generally confirmed the ship performance trends identified numerically from the idealised ship trials conditions. Furthermore, the responses from the ship masters provided much additional information on the relative performance of the vessels in a wide range of operational situations not covered by full scale trials data. In many cases further assessments of a qualitative nature but still of practical importance were achieved.

Prominent among the results of the interview analysis was an appreciation of the complex interplay of ship performance requirements, and by association ship design features, for the effective and efficient conduct of missions, notably of ice escort. The ultimate objective of the designer, owner and operator is to provide the " best" ship to satisfy the requirements. The strength of the interview process lies in bridging the gap between design and mission performance such that pro-

cesses may be developed for identifying the best ship for a particular service in terms of design and performance relationships in various modes of operation. It is determined from the results of the interview process that the current state of knowledge is suitable to address the process of defining escort efficiency in terms of ship design and operation.

The interviews also identified seakeeping as an important element in their assessment of overall vessel performance. However, no seakeeping trials data are available for any of the vessels in the study. It is therefore considered that this performance aspect should receive attention.

It is concluded that this project has provided a unique set of information, based on full scale ship performance, for predicting the performance of icebreakers in clearly specified conditions. This provides the designer and operator with the practical tools for improving design and operation. Furthermore, considerable progress has been made in understanding the next logical development stage of how overall performance in the mission context can be measured and translated into design.

SOMMAIRE

Ce rapport fait le point sur l'influence de certains paramètres tels que la forme géométrique de la coque, les caractéristiques du système propulsif et de l'appareil à gouverner sur les performances des brise-glace, dans des conditions environnementales variées, à partir des résultats d'essais dédiés en vraie grandeur et des interviews auprès des commandants et se rapportant à seize des brise-glace les plus représentatifs et les plus modernes.

Les équations ou modèles mathématiques qui ont été élaborés à la suite de cette recherche permettent désormais de prédire les qualités de déglaçage, de giration ou de marche en eau libre d'un brise-glace durant le processus de conception. De plus, des progrès intéressants ont été faits dans l'approfondissement des liens entre les performances mesurées dans les conditions théoriques que représentent les essais, d'une part, et, d'autre part, dans les performances globales dans les conditions environnementales réelles auxquelles les brise-glace sont normalement soumis.

La phase antérieure de cette recherche (voir le rapport TP 9992E, référence 91), avait permis d'approfondir l'influence des paramètres de conception sur les performances de six brise-glace modernes, ainsi que celle des caractéristiques conceptuelles novatrices qui les distinguent. Il s'agissait principalement de brise-glace marchands canadiens opérant dans la mer de Beaufort, conçus pour appuyer les opérations de mise en valeur des richesses naturelles au fond de la mer Arctique, notamment les opérations de maîtrise des glaces et de remorquage, d'ancrage et d'approvisionnement des plates-formes de forage. Déplaçant jusqu'à 7 000 tonnes et mus par une puissance à l'arbre jusqu'à 17 mégawatts, ces navires sont caractérisés par un avant court, ayant un angle de dévers prononcé, des lisses d'angle, des renflements latéraux angulaires ou arrondis, ainsi que des systèmes de propulsion à hélices à pas variable sous tuyère ou non. Les essais avaient eu lieu dans des glaces de l'année de forte résistance, et parfois aussi dans des glaces moins froides et de moindre résistance, au début ou à la fin de la saison d'hiver.

La phase 2 de la recherche a porté sur un nombre plus élevé de navires construits un peu partout dans le monde et destinés surtout à jouer le rôle traditionnel d'escorteur. Ont été représentés, tous les navires ayant une cote arctique de quelque importance et appartenant à la Garde côtière canadienne ou à celle des États-Unis, le cargo brise-glace M.V. Arctic et les brise-glace les plus récents conçus en Europe et opérant dans la Baltique. En tout, les navires analysés appartenaient à dix classes différentes et représentaient 12 modèles distincts, si l'on compte que deux ont été entièrement ragréés. En règle générale, ils sont de conception assez traditionnelle, destinés à opérer en eau libre et dans les glaces, pourvus d'une coque à formes pleines et d'un avant plus long présentant un angle de dévers moins prononcé. Leur système propulsif est soit du type à hélices à pas fixe sans tuyère, soit du type à hélices à pas variable sous tuyère ou non. Seuls deux navires de conception plus moderne ont fait exception à cette règle. Ces navires ont jusqu'à 40 000 tonnes de déplacement et 45 mégawatts de puissance à l'arbre. Les essais ont eu lieu dans des conditions glacielles variées, allant des glaces d'eau douce de première année aux glaces d'eau de mer, moins froides et affaiblies par le dégel, selon le cas.

Les résultats des phases 1 et 2 de la recherche, combinent la saisie de données sur les performances lors d'essais dédiés en vraie grandeur, leur analyse et l'analyse des interviews. Ils couvrent pratiquement toute la gamme des paramètres caractérisant les brise-glace: taille, puissance, caractéristiques, conditions environnementales, état de la coque, catégories de performances et rôle opérationnel. La base de données ainsi obtenue constitue le corpus d'information à analyser le plus complet et le plus fiable à ce jour.

Les données de la phase 2 de la recherche ont été converties au même coefficient sans dimension que celui dégagé durant la phase précédente, fusionnées aux précédentes et soumises à une analyse visant à approfondir l'influence des paramètres de conception et d'environnement sur les performances. L'analyse a porté sur les mêmes catégories de performances que dans la phase 1, à savoir: marche dans des glaces uniformes, rendement du système propulsif, franchissement de crêtes de pression, qualités manoeuvrières, progression dans un chenal ouvert, performances en conditions glacielles variées, interaction hélices-glaces et marche en eau libre. Cette démarche a débouché sur l'élaboration de modèles mathématiques de type empirique pour la prévision des performances, selon différentes combinaisons de caractéristiques conceptuelles, de paramètres de forme de coque et de conditions environnementales.

Les interviews menées auprès des commandants ont permis de récolter une information qualitative sur les performances de leur navire respectif dans des conditions environnementales non représentées lors des essais dédiés, et d'approfondir davantage les relations complexes existant entre caractéristiques conceptuelles, performances locales dans des conditions glacielles variées et performances globales, en fonction des missions entreprises par le navire.

Eu égard à la vaste gamme de paramètres pris en compte comme la forme du navire, les conditions environnementales et les missions exécutées, l'analyse des performances, objet de la recherche, a permis de constituer un corpus d'information tant qualitative que quantitative, aussi complet que possible, sur le comportement des brise-glace.

Cette analyse a montré que l'influence des paramètres sur les performances, mise en évidence par la phase 2, est la même que celle dégagée par la phase 1 (TP 9992E), compte tenu du contexte beaucoup plus vaste de cette deuxième phase. Sa portée, beaucoup plus large que la précédente, a permis d'approfondir l'influence de toute la gamme de paramètres de conception, de conditions environnementales, de catégories de performances et de rôles sur le comportement d'un nombre plus grand de brise-glace.

L'analyse des performances dans des glaces uniformes a fait ressortir la faiblesse du procédé généralement utilisé de calage des résultats à partir du seul paramètre de résistance à la rupture en flexion des glaces, dans le but de tenir compte des variations dans les conditions environnementales. C'est ainsi qu'il a fallu tenir

compte du facteur température à la surface de l'eau, qui détermine les forces de frottement, et de la salinité des glaces, qui conditionne l'énergie totale absorbée par le processus de déglaçage. Les données, une fois corrigées en fonction des résultats des recherches les plus récentes et de celles qui se poursuivent, ont permis d'élaborer une base de données qui fait ressortir des liens à la fois logiques et cohérents entre paramètres de conception et performances. Cette technique permet d'exploiter n'importe quelle base de données tirées d'essais dans des glaces uniformes pour établir des bilans comparatifs de performances, les conditions environnementales étant par ailleurs comparables.

Il a été constaté que la résistance à la marche dans des glaces uniformes est surtout influencée par les angles de dévers et les angles des sections longitudinales caractéristiques de l'avant, qu'elle l'est fortement aussi par le bau et, dans une moindre mesure, par la longueur et le tirant d'eau. De plus, les navires à lisses d'angle montrent qu'ils ne sont pas aussi sensibles à un accroissement de l'épaisseur des glaces que ne le sont les navires à formes pleines.

L'analyse des performances dans des crêtes de pression a mis en évidence pour la première fois le paramètre de forme géométrique influençant l'énergie absorbée par cette opération: l'accroissement de l'angle de dévers améliorant sensiblement les performances à ce chapitre.

La grande efficacité des techniques de lubrification de l'interface glace-proue pour la réduction de la résistance à la marche dans des glaces uniformes, constatée lors de la phase 1, est maintenant confirmée. Il en est de même pour les techniques d'injection d'air ou d'eau sous pression.

La recherche a également permis d'analyser les performances en marche avant du système propulsif des brise-glace lors des opérations de déglaçage. Ainsi, ont été confirmés les gains appréciables autorisés par les tuyères et la souplesse opérationnelle des hélices à pas variable sans tuyère, dont les performances sont relativement élevées à des vitesses nettement supérieures aux vitesses nominales courantes de déglaçage.

La recherche a montré qu'il est possible de cerner de près les qualités giratoires dans les glaces des navires comportant des renflements latéraux, celles-ci étant conditionnées par la forme géométrique de la coque exprimée par le rapport largeur du renflement à la longueur de la section rectangulaire médiane du navire. Un grand progrès a été réalisé vers une connaissance plus fine des qualités giratoires des navires de forme classique, ne comportant pas de renflements latéraux, leurs performances étant fortement tributaires à la fois de la forme géométrique décrite comme étant le rapport en pourcent de la longueur de la section rectangulaire médiane à la longueur totale du navire, et de l'efficacité relative de l'appareil à gouverner.

Quant à la résistance à la marche en eau libre, l'analyse a montré que pour les brise-glace de forme moderne comportant des lisses d'angle et des renflements latéraux arrondis ou angulaires, elle est sensiblement plus élevée, - de près de 100 p. 100 -, que celle des navires de forme plus classique, c'est-à-dire pleine, de taille et de coefficients de forme comparables.

Les interviews auprès des commandants de ces navires ont permis de confirmer les tendances que les données numériques tirées des essais dédiés en vraie grandeur ont mises en évidence. De plus, elles ont fourni un supplément d'information se rapportant aux performances des navires dans des situations que les essais n'ont pas pu couvrir; dans certains cas, elles ont conduit à des évaluations qui, bien que qualitatives, n'en sont pas moins éminemment utiles.

Un des résultats les plus intéressants de cette démarche directe auprès des commandants a été une appréciation des interrelations complexes entre les diverses exigences en matière de performances et les éléments de conception adoptés pour les satisfaire et permettre l'exécution efficace des missions que ces navires sont appelés à remplir, notamment celle d'escorteur. Architectes navals, armateurs et commandants poursuivent le même but: réaliser le navire représentant le meilleur compromis entre toutes les exigences définies. Les interviews sont donc d'autant plus utiles qu'elles parviennent à mieux cerner l'écart entre les performances nominales et celles obtenues en situation opérationnelle, et qu'elles débouchent sur une démarche permettant de définir le navire le plus approprié, en fonction de sa forme, de ses performances et des missions à exécuter. Les interviews permettent ainsi aux chercheurs d'exprimer l'avis que, vu l'état actuel des connaissances, il est désormais possible de traduire les exigences en matière d'efficacité dans le rôle d'escorteur d'un navire en paramètres de conception et d'exploitation.

Autre facteur d'importance que les interviews ont révélé, celui des qualités nautiques globales du navire. Or, étant donné qu'on ne dispose pas de résultats d'essais permettant d'évaluer les brise-glace sous cet angle, il est recommandé que cet aspect de la question soit approfondi.

Les chercheurs considèrent que l'étude a permis de dégager un jeu unique de données sur les performances réelles des brise-glace pouvant servir d'outil prédictif des performances dans des conditions clairement définies, outil dont se prévaudront les architectes navals et armateurs pour améliorer les paramètres de conception et d'exploitation. De plus, ils considèrent avoir fait de grands progrès vers la définition de la phase suivante et logique de la recherche, celle qui montrera comment les prévisions concernant les performances globales dans telle ou telle condition d'exploitation pourront être chiffrées et traduites en paramètres de conception.

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LIST OF SYMBOLS

A_C = largest hull cross sectional area (below waterline for ridge penetration) (m^2)
A_R = ridge length * ridge profile length (rubble only) (m^2)
B = ship beam at waterline (m)
C_{flare} = factor for ice resistance dependency on bow average flare angle
$C_{buttock}$ = factor for ice resistance dependency on bow average buttock angle
C_H = hull condition factor (Inerta = 1, new bare steel = 1.33)
C_O = ice strength factor
C_S = water salinity factor (saline = 1, brackish = 0.85, fresh = 0.75)
C_t = friction/temperature (ice surface) factor
D = turning circle diameter (m)
Disp = ship displacement (tonnes)
E = Young's modulus
E_R = energy for ridge penetration (rubble only) (MJ)
f = flexural strength index (kPa)
F_n = Froude number
H = ice thickness (m)
L_{WL} = waterline length of ship (m)
MCR = maximum continous rating (of ship's propulsion plant
PMB = percentage of waterline length representing parallel midbody
R = open water resistance (MN)
R_{ice} = resistance in ice (MN)
R_1 = resistance in level ice at 1 m/s
S = salinity of melted ice core (parts per thousand)
t = ice surface/air temperature (^{o} C)
= thrust deduction factor (Appendix C)
T = ice core temperature (Chapter 2) (^{o} C)
= draft of ship (Chapter 11) (m)
V = ship speed (m/s)
V_b = brine volume of ice
x = reamer width as a percentage of parallel midbody length
σ_f = flexural strength of ice (kPa)
φ = average buttock angle over the bow (degrees)
ψ = average flare angle over the bow (degrees)

1.0 INTRODUCTION

1.1 Background

A previous project [91] was carried out for Transport Canada, Transportation Development Centre, with the objective of analyzing the performance of predominantly Beaufort Sea icebreaking technology. The project included a comprehensive analysis of all full scale performance data for six major icebreaker designs, as well as interviews with their masters, in order to determine their practical operational performance. These ships had all been designed using an innovative simple approach to hull design, utilizing chines, some reamers, wedges under the bow, vertical parallel sides, as well as controllable pitch propeller geared drive propulsion systems, mainly with nozzles but also some without.

The operational missions for these ships were ice defence, anchor handling, supply and towing operations, and to a degree escort duties. Thus the basic requirements for design were quite different from those of traditional icebreakers elsewhere in the world. Traditional missions typically priorise operations such as ice escort and often icefree transits. The project, "Icebreaker Design Synthesis" [91], thus analysed the performance of the Beaufort Sea technology for specific performance components of the ships investigated on full scale trials, as well as the operators' experience of their capability in operational situations.

The project "Icebreaker Design Synthesis" [91] achieved success in establishing many of the influences of design upon both specific performance components and operational performance for vessels incorporating Beaufort Sea technology. On completion of the project, it was decided that in order to be of the maximum value to the Arctic marine community, the study should be extended to include vessels incorporating the much wider range of parameters and features of icebreakers having more traditional roles.

1.2. Project Overview

The current study, Icebreaker Design Synthesis, Phase II, is an extension of the adopted approaches from "Icebreaker Design Synthesis". Following the success with the analysis of data and operator interviews, Transportation Development Centre commissioned this project. The intent was for this study to merge all the data and further interview results for more traditionally operated icebreaking ships such as those of the Canadian Coast Guard, US Coast Guard, as well as extensive international coverage. This included recent Baltic icebreakers and the latest German design Mudyug for Soviet operations. The additional vessels therefore covered the latest state of the art developments on an international basis of both traditional and innovative icebreaker technology. The scope of the inter-

views was extended to cover those missions not normally included in commercial offshore operations, such as,

- Buoy handling
- Search and Rescue

Other operational missions were kept the same as the previous project, even though changing order of priority, namely:

- Escort
- Towing
- Ice management
- Supply

The ship trials performance categories, out of which components the mission profiles are built, were the same as before:

- level ice performance
- ridge performance
- broken ice performance
- manoeuvring performance
- pressure or dynamic ice performance
- open water performance
- propulsion performance
- transit performance

The ship trials performance data were obtained in a very wide range of both environmental conditions, from cold, strong fresh ice to warm, weak saline ice, and hull conditions. Consequently it was not possible to determine the influence upon performance of design features and parameters without first correcting to a common environmental and hull condition. All data for both the previous and this project were merged, corrections were made and the total database was analysed for the influence of design upon performance.

The overall objective is to arrive at designer usable methodologies for assessing the performance of any particular type of ship with given design features, size and power. The operational experience from the interviews is intended to help in assessing the feasible design feature selections for a particular mission role. In order to facilitate this process, interactive software programs are developed for performance component calculations.

The outline of the project report is given below:

Chapter 2. Background information of the ships, the tests and the environment

Chapter 3. Operator Interview

Chapter 4. Level Ice Performance Ahead

Chapter 5. Channel Performance

Chapter 6. Manoeuvring Performance

Chapter 7. Open Water Performance

Chapter 8. Ramming Performance

Chapter 9. Transit Performance

Chapter 10. Propeller/Ice Interaction

Chapter 11. Mathematical Models

Chapter 12. Conclusions

Chapter 13. Recommendations

Chapter 14. References

2 BACKGROUND INFORMATION

2.1 Ships

This project involves the study of the following icebreaking ships, in association with the Contemporary icebreakers Kigoriak, Robert Lemeur, Terry Fox, Ikaluk, Arctic Ivik and Max Waldeck from Icebreaker Design Synthesis Phase 1 [91].

'R' Class (Pierre Radisson *, Franklin and Henry Larsen *) - CCG
Louis S. St. Laurent * - CCG
John A. MacDonald * - CCG
'1100' Class (Ann Harvey, Martha Black * and Edward Cornwallis *) - CCG
Earl Grey * ('1050' Class) - CCG
Polar Class (Polar Star * and Polar Sea) - USCG
Bay Class (Katmai Bay and Mobile Bay) - USCG
Arctic * - Canarctic Shipping Company Limited
Polarstern - Bundesministerium fur Forschung und Technologie (Germany)
Otso and Kontio - Finnish Board of Navigation
Oden - Swedish National Maritime Administration
Mudyug - MORFLOT (North Sea Shipping - USSR)

* Interview conducted with master

With the exception of the Arctic and the Polarstern, all of the ships have been designed with ice escort as one of the primary missions. The Arctic is a combined oil/bulk carrier. The Polarstern's primary mission is scientific research in ice covered waters. Figure 2.1 shows the general arrangements of each of these ships, as well as the ships studied in Phase 1 of this project. Table 2.1 gives relevant details of the ship design particulars regarding dimensions, powering and steering arrangement.

To understand the design and operation of each of the ships a brief description of the design mission roles and the key design features is given below. Further details of the ships chosen as subjects for the interview are given in Appendix B.

'R' Class

The primary missions for the 'R' Class are ice escort and ice management in the Gulf and River St. Lawrence, in the Great Lakes and in the Canadian Arctic. Secondary missions are Search and Rescue (SAR) and supply. The Henry Larsen is an improved version of the earlier ships of the class, with Arctic class 4 capability, more power, an Intering heeling system, AC/AC propulsion and a bubbler.

They are diesel electric twin screw ships with a bow

improved over the earlier CCG major icebreakers by decreasing the stem angle and increasing the flare at the bow. The first three ships of the class are expected to operate on a draft of 6.3 m in the Great Lakes.

Louis S. St. Laurent

The primary missions are ice escort and ice management in the Gulf of St. Lawrence and the Canadian Arctic. Secondary missions are SAR and supply.

She is a triple screw ship powered by a turbo-electric propulsion plant, incorporated to give the operators experience for a future Polar class nuclear icebreaker. The bow and stern are "traditional" forms with low flare angles and she has a high bow stem angle. The beam was increased over earlier ships to provide easier escort for larger ships. The high fuel consumption necessitates frequent operation at drafts exceeding the design draft to carry a sufficient reserve of fuel.

John A. MacDonald

Missions and areas of operation are similar to the St. Laurent.

She is a triple screw ship powered by a diesel electric power plant. The hull form is similar to that of the St. Laurent, but she does not have a bow stopper. Her Arctic duties (and those of the present heavy CCG icebreakers including 'R' Class and St. Laurent) involve following and forcing leads and avoiding heavy icebreaking wherever possible. Considered by CCG to be an effective icebreaker for her assigned role.

'1100' Class

The primary missions for this class are buoy handling and supply on both coasts of Canada and ice escort in the western arctic and Gulf of St. Lawrence. A secondary mission is SAR.

They are classed as large navaids tender/light icebreakers and are designed to operate in ice accessible by ASPPR Class 2 vessels. The twin screw propellers are driven by an AC/AC diesel electric system operating as a central power plant. They have a transom stern and a bow form designed as a compromise between open water and ice duties.

'1050' Class

The primary missions for this class are buoy handling and ice escort and management. They operate in both the Gulf of St. Lawrence and the Great Lakes. SAR is a secondary mission.

They are designated as medium navaids tenders/light icebreakers and the design is based on an offshore supply vessel configuration. They therefore have a transom stern and have

high freeboards forward and low aft. The bow has been designed for icebreaking and incorporates a 25 degree stem angle with a small stopper. They are twin screw with controllable pitch propellers and nozzles and have an installed power of 6680 kW.

Polar Class

The primary missions are ice management and ice escort in both Antarctic and Arctic waters. Secondary missions are research and supply with SAR performed on an as required basis. Lately missions in ice covered waters in support of research have become increasingly important.

They are powerful triple screw icebreakers (14.9 MW per shaft) with controllable pitch propellers. The power plant can be operated in a diesel electric mode up to 13.4 MW and in a gas turbine geared drive mode up 44.7 MW. A 'White' bow was fitted to reduce resistance. Significant propeller/ice interaction restricts the use of the full power.

Bay Class

Although designated as multi-mission cutters (SAR, towing, and law enforcement), they were primarily designed as icebreakers for service on the Great Lakes.

They are single screw diesel electric ships with an improved bow incorporating high flare angles in the bow. To reduce friction in the mixed ice conditions in which they operate and increase the escort effectiveness, they are fitted with a bubbler.

Arctic

The Arctic was originally designed as CASPPR class 2 to operate independently in ice in Baffin Bay, Lancaster Sound and Admiralty Inlet carrying bulk cargoes. She was upgraded by fitting a new bow, incorporating midship structural improvements and converting the holds for oil/bulk cargoes. The new configuration and ice class 4 enabled her to carry crude cargoes from Bent Horn.

She has a single controllable pitch propeller fitted in a nozzle. The new bow has high flare angles carried well aft. Although fitted with a bubbler, it has proven unreliable in service. The ship has a long parallel midbody to maximize cargo deadweight, as the beam was restricted by the requirement to transit the Seaway.

Polarstern

The primary missions of the vessel are research in ice covered waters and supply of the German Antarctic Station once each year.

She has twin controllable pitch propellers fitted in nozzles close to the centreline and deeply immersed. The hull lines were designed to minimize the ingestion of ice into the propellers. The shoulders were designed to break ice in bending as far aft as possible and the lower part of the forebody was designed to push ice sideways.

Otso/Kontio

This class of icebreaker performs ice escort duties in the Baltic Sea. This mission involves towing. Ice management is a secondary mission. The vessels occasionally perform buoy handling duties and SAR.

They have twin fixed propellers and twin rudders. The diesel electric power plant generates a total of 21.8 MW with the propulsion motors rated at 7.5 MW each. The ships are fitted with bubblers. The ships were designed to have a convoy speed in average ice conditions of 8 to 10 knots, with the capability of breaking average ridges without ramming. They were designed to break ice and manoeuvre effectively astern. The ships have a shallow stem angle (20 degrees) and the bottom has a rise of floor to minimize ice ingestion into the propellers.

Oden

The Oden's primary winter mission is ice escort including towing in the Baltic Sea. Secondary missions include ice management and buoy handling. SAR and supply are performed occasionally. The ship was given additional hull strengthening to allow her to make Arctic voyages in the summer when the Baltic is ice free.

The Oden is a further development of the Beaufort Sea icebreaking technology. She has twin controllable pitch propellers in nozzles driven by geared diesel engines. The hull is fitted with reamers and secondary turning reamers to improve the manoeuvrability. To minimize ice ingestion into the propellers the stern is 7.5 m narrower than the midbody and the ship has a wedge forward. The beam over the main reamer is 29.4 m, considerably wider than other Baltic icebreakers. This improves the track for the following ship and enables tighter manoeuvring of the escorted ship(s).

Mudyug

The primary missions of the Mudyug are ice escort and ice management in the White Sea. In addition she has performed escort duties on the Soviet North East Passage.

The Mudyug incorporates a Thyssen Wass bow on a conventional medium icebreaker and is a further development of the bow first demonstrated on the Max Waldeck (see phase 1 report).

The stern which was not changed has twin controllable pitch propellers driven by a geared diesel plant and has twin rudders. The stem angle is very low (12 degrees) and the bow has runners and reamers. The bow is lubricated with water and water/air jets located above and below the waterline and the runners have a high pressure water jet to prevent ice sticking.

2.2 Trials

The Trials Matrix, Table 2.2, provides a listing of all those ship trials in ice which provided data for use in the performance analysis. All trials were dedicated solely to testing the ships.

The list was compiled following a thorough reference search and review of material for completeness and quality. In a few cases, trials data could not be used in the analysis, principally on the basis of a lack of reliable environmental information. These cases are documented in the respective performance sections of this report. The Phase 1 trials information is included in Table 2.2 for completeness.

Table 2.2 provides the date and location of each trial series and the types of performance tests in ice which were conducted. Open water power versus speed tests have also been conducted on all vessels. All reports are referenced for each case vessel.

The general hull conditions at the time of the trials are listed. Of the new Phase 2 group of vessels, all except the R-Class, Louis St. Laurent and Otso were coated over the full hull with Inerta and the trials were conducted within at most 2 years of application. The R-Class vessels, Franklin and Pierre Radisson, were tested with bare steel hulls within one year of their delivery. Louis St. Laurent had an Inerta coating in a belt around the waterline only. Elsewhere, the hull was bare steel. Otso had a 2 metre belt of stainless steel around the waterline with full Inerta coating elsewhere.

The degree of deterioration of the hull surfaces at the time of the trials was generally not well recorded. This can have an important influence, particularly upon ice resistance. The assumptions and methodology employed to account for hull deterioration is given in Chapter 11.

The ship trials were not necessarily carried out at the design drafts given in Table 2.1. A separate Table 2.3 is therefore provided giving the vessel trials parameters. These parameters describe the dimensions and geometry of the vessels in simple practical terms suitable for performance analysis and preliminary design.

The data in Tables 2.1 and 2.3 provide a clear picture of the wide range of ship design parameters incorporated in the project group of icebreakers. This is emphasised in Figures

2.2, 2.3 and 2.4, where respectively, ship displacement is plotted versus shaft power, parallel middle body length is plotted versus waterline length and the average bow flare angle is plotted against average buttock angle (both averaged across the beam). The vessel group covers ship lengths from 40 up to 211 metres, ship displacements from 660 up to 39000 tonnes, total power from 1.9 up to 45 megawatts, parallel middle body length from zero to 80% ship length, average buttock angles from 16 up to 40 degrees and average flare angles from 25 up to 90 degrees.

Moreover, as noted above, hull forms covered by the group are fully formed, chined and reamered with additional features covered of bow wedges, buttock and waterline flow afterbodies, cruiser and transom sterns, flat bottoms and high rise of floor.

The propulsion and steering arrangements cover single, twin and triple screws with single rudder and twin screws with twin rudders. Fixed pitch and controllable pitch propellers and propeller nozzles are fairly evenly represented.

It can therefore be considered that the group of vessels for which reliable trials data are available to the project provides excellent coverage of virtually all ship design parameter ranges and features incorporated in icebreakers.

2.3 Environmental Data

2.3.1 Introduction

As in phase 1 of this project, all of the ships in this study have been tested in different locations, at different times of the year and in different years. In addition, the water in which the ice was formed, varied from fresh water (Great Lakes and Saguenay River), to brackish (Lake Melville and Baltic Sea) to salt water. In order to make valid comparisons of the performance data, the environmental conditions should be analyzed to determine the similarities and differences and where feasible make corrections to the performance data to bring the data to a common base.

It is well known from model tests and full scale trials that ice thickness, ice strength, and friction all have a major impact on the performance. In addition other environmental factors such as wind speed and direction relative to the vessel's direction and air temperature have an influence on the performance.

A summary of the environmental data for the ship trials is given in table 2.4. The analysis of the environmental data collected during the trials is contained in Appendix A. The following sections contain a discussion of the major issues concerning interpretation of the environmental data.

2.3.2 Ice Strength

The ice strength data for the ship trials in this study has been assessed in a number of different ways in the original reports. Temperature/salinity profiles have been collected for some trials and the flexural strengths calculated using different formulae. Beam tests have been conducted to assess the flexural strength with the quoted values based on different numbers of tests (varying from 1 to 15). The Katmai Bay strength data was assessed from the ice temperature and a standard curve of temperature versus strength. The Mudyug trials quote strength data, but do not give the method used to calculate the value nor do they give the associated environmental conditions. Some of the trials included both temperature/salinity profiles and beam tests.

Where temperature/salinity profiles were available, it was decided to compare the ice strengths of the various ship trials on the basis of a flexural strength index, calculated on a standard basis from temperature/salinity profiles. This method is set out below.

Based on discussions with IMD, the following methodology was used to calculate a flexural index strength from the temperature/salinity profiles:

1) Use the formula below to calculate the brine volume at each level from the temperature/salinity readings;

$$Vb = S*(0.532 - 49.185/T) \qquad -22.9 < T < -0.5$$

where Vb = brine volume
S = salinity
T = temperature

2) Take the average of the brine readings over the full depth.

3) Using the average brine volume calculated in 2) calculate the flexural strength index from the following formula;

$$f = 850*(1 - 0.072*Vb^{**}0.5)$$

where f = flexural strength index (KPa)
For Vb greater than 131, flexural strength index is assumed to be less than 150 kPa.

The flexural strength values given in table 2.4 have been calculated on this basis unless the comments column notes either a beam test or some other source (Mudyug or Katmai Bay).

Beam tests were conducted on a number of the trials as shown in table 2.4. Where available, the flexural strength indices are compared with the beam tests. Other strength

indices such as bore hole jack, flaking tests and fresh water ice strength from temperature are also given. For some of the beam tests, Young's modulus (E) has been given or calculated from the available deflection data.

The table shows that the beam tests give a higher flexural strength index than the index calculated from the temperature/salinity profile in all cases other than the M.V. Arctic trials in Lake Melville in 1981. The salinity value is suspect as it is much lower than values taken in other years at the same time [10]. Young's modulus varies with the type of water from which the ice was formed; salt water being lowest with values of 1300 to 1400 MPa, brackish water next with 2300 MPa and fresh water the highest with values of 5700 MPa. This conclusion is based on a limited number of samples and must be tempered with the fact that the saline water ice was tested at lower temperatures. It is well known from model tests that the ratio of E to flexural strength has a marked effect on resistance. The comparison of resistances on the basis of strength data alone, when the Young's modulus is likely to vary, should be treated with caution.

The salinity of the water from which the ice was formed determines the crystallographic structure of the ice. This structure will influence the mechanical properties of the ice. In the present study, trials have been conducted in areas which are known to have lower salinities, although none of the tests recorded the salinity of the water. These include; Lakes Michigan and Superior (fresh water), Saguenay River (brackish), St. Lawrence River (fresh to salt water depending upon location), Lake Melville (brackish) and the Baltic Sea (brackish). Brackish water has salinities ranging from 0.5 to 17 parts per thousand. Typical salinities are given in the table below:

Area	Parts per thousand
Saguenay R. - Port Alfred	4
St. Lawrence - Quebec	0 (fresh)
- Off Saguenay R.	20 to 25
- Matane	29 to 30
- Gulf St. Lawrence	30 to 32
Lake Melville	6 to 19
Baltic Sea (northern end)	3.5

The values in Lake Melville vary throughout the season, but the lower salinities are found consistently at the western end of the lake where there is a large inflow of fresh water from the Churchill River. The constant flow of ice down the St. Lawrence River means that any testing which occurs in floes in one area of the river, may not be in ice which was formed in that area. Hence it may have been formed from water of lower salinity.

At present, the authors are not aware of data that would tie the ice properties to a variation in water salinity such

that the change in properties could be used to determine the influence on the ice resistance of the tested ships.

2.3.3 Environmental Data

As reflected in the formula for the calculation of flexural strength index from temperature/salinity profiles, the temperature of the ice affects the strength. The ambient air temperature will affect the ice temperature, but the extent to which the air temperature modifies the ice strength depends on a number of factors such as the ice and snow thicknesses, the duration of the temperature and the presence of sun. In general the ice strength data in table 2.4 reflects the seasonal variation of temperature. However some of the strength data is suspect as the ice strength was assessed before the trials were conducted. This was the case for the M. V. Arctic 1986 Strathcona Sound trials and the Louis S. St. Laurent 1979 trials. These trials were conducted at a time of the year when the ice was observed to be degrading with time. The effect can not be quantified based on the available information. An example of the degradation of ice strength with increase of temperature is given from measurements made during the trials of the Ann Harvey in March 1989 where the ice strength went from 330 kPa to 153 kPa in 6 days due to several warm sunny days [71].

The surface of the ice or snow responds much more rapidly to the change in air temperature than the main body of the ice from which the temperature/salinity profiles are taken. This can affect the friction factor between the ship and the ice. Trials with large variations in temperature include the Pierre Radisson 1979 St. Lawrence (-23 to -1), the Polar Star 1982 Bering Sea (-18 to +2) and the Katmai Bay (-7 to -23).

As can be seen from table 2.4, the snow thicknesses in all the trials varied from 0 to 0.52 m. This wide variation in snow thickness in conjunction with the variation in temperatures, is expected to have a major effect on the friction and hence the resistance. As it is not possible to quantify this effect, the snow has been accounted for by including one half its thickness in the total ice thickness as was done in phase 1.

Wind speeds have been reported in only about 50% of the trials. In some of the trials (Polar Star in the Bering Sea and Pierre Radisson in the St. Lawrence River), the wind speeds were in the range of 15 to 18 m/s. As was demonstrated in the phase 1 study, high winds especially in thinner ice and at low ship powers can have a large effect on the resistance depending upon the wind direction relative to the ships heading. The data as presented does not include the wind direction and the ships heading, making it impossible to correct the data.

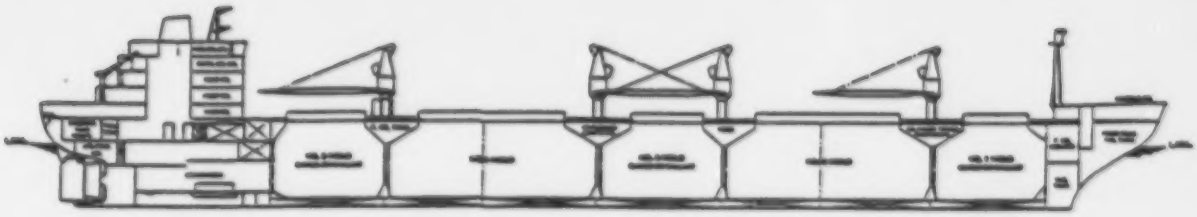
The winter 1979 trials of the Pierre Radisson in the St. Lawrence River include elements of all the above variations in environmental data as shown in table 2.5. The water varied from brackish in the Saguenay to salt in the Gulf of St. Lawrence.

Although the air temperatures varied from -30 to +4, the reported ice strengths were in a relatively small range 404 to 523 kPa as determined from beam tests. Snow thicknesses varied from 0 to 0.143 m. Wind speeds were as high as 17 m/s and although the time of the higher winds is reported, the time of the trials is not. Although the wind direction is reported, the ships heading is not.

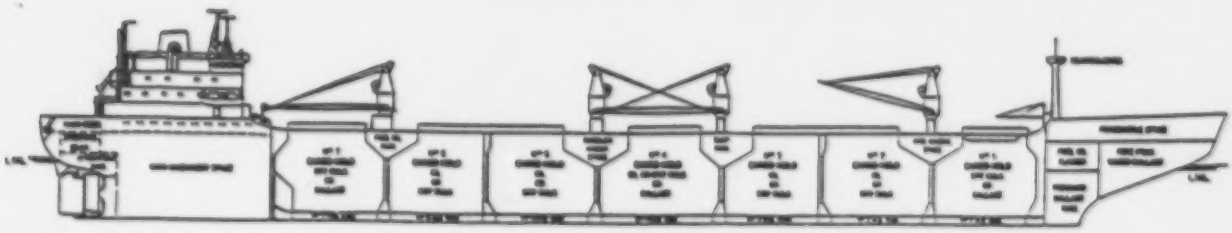
The Beaufort Sea winter trials reported in Phase 1 were conducted in a narrow range of environmental conditions as shown below:

- all trials conducted in the Beaufort Sea (saline)
- all air temperatures below -20 degrees C.
- maximum snow thicknesses of 0.20 m.
- low wind speeds or wind speeds and directions and ships headings accounted for.
- Temperature/salinity profiles given for all the trials to enable the strength data to be compared.

This is clearly not the case for the data sets in the present study. Care must therefore be taken in interpretation of the data points for individual trials where different ice thickness data points were collected in different environmental conditions. In addition, as there are wide variations in the environmental conditions associated with the data sets for different ships, comparisons between ships should be made only for those ships with similar environmental conditions.



Arctic (Old Bow)



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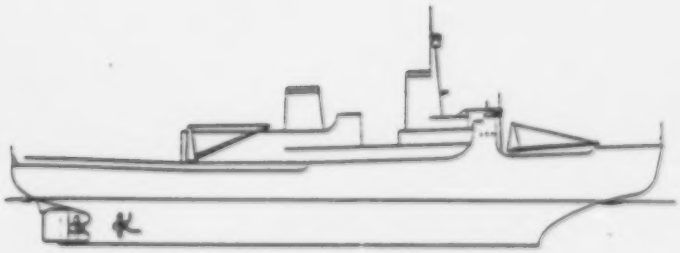
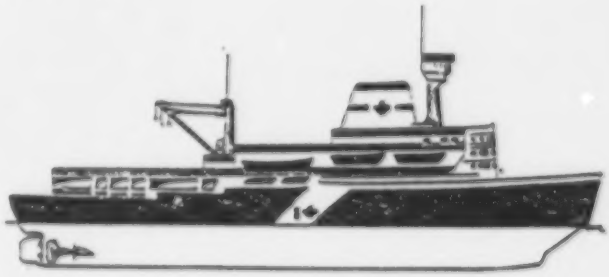
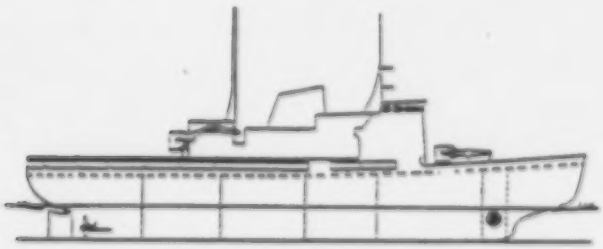


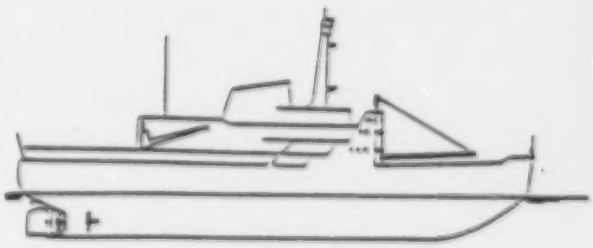
Polar Star / Polar Sea



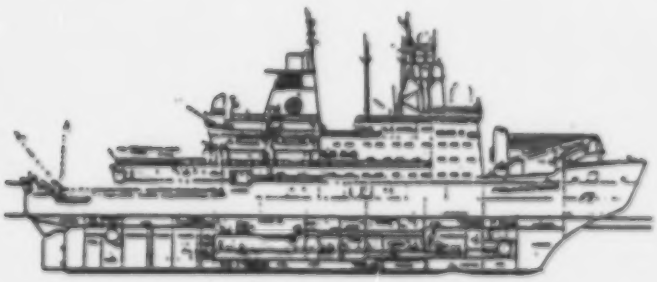
Louis S. St. Laurent



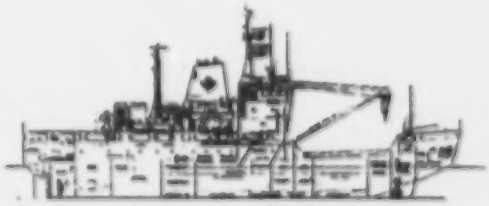
"R" Class



John A. MacDonald

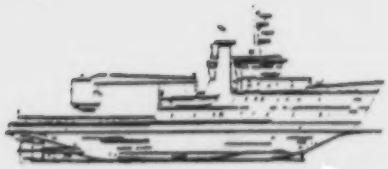


Polarstern



1100 Class

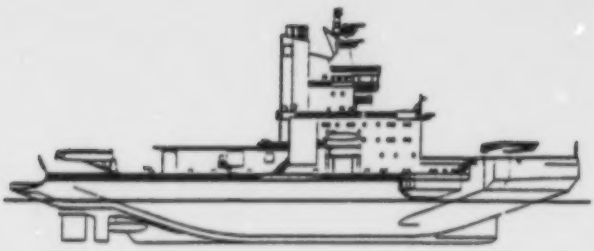
Figure 2.1 Ship Profiles



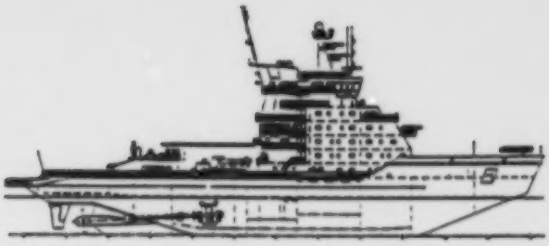
1050 Class

Bay Class

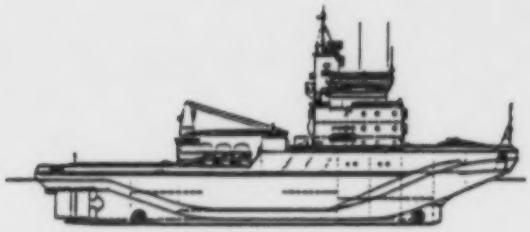
Figure 2.1 (continued) Ship Profiles



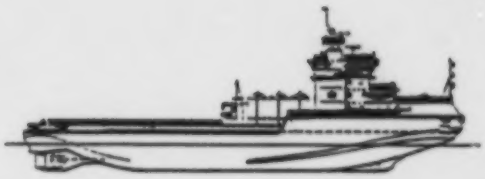
Oden



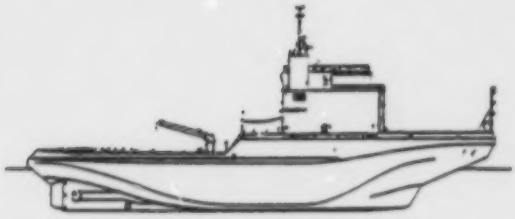
Kontio / Otso



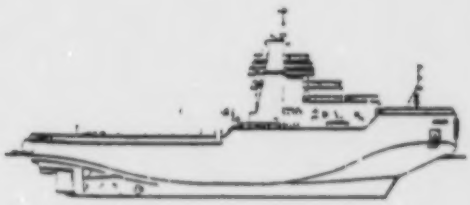
Kigoriak



Robert Lemeur



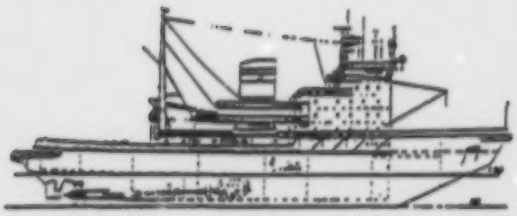
Terry Fox / Kalvik



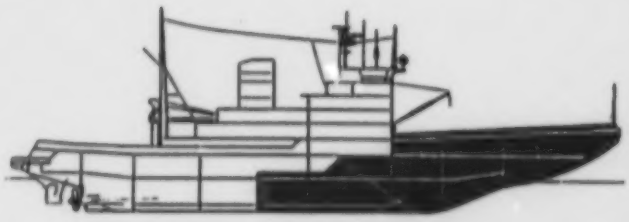
Ikaluk / Miscaroo

Arctic Ivik

Max Waldeck



Mudyug (Old Bow)



Mudyug (New Bow)

Figure 2.1 (continued) Ship Profiles

FIGURE 2.2
RANGE OF DISPLACEMENT AND SHAFT POWER

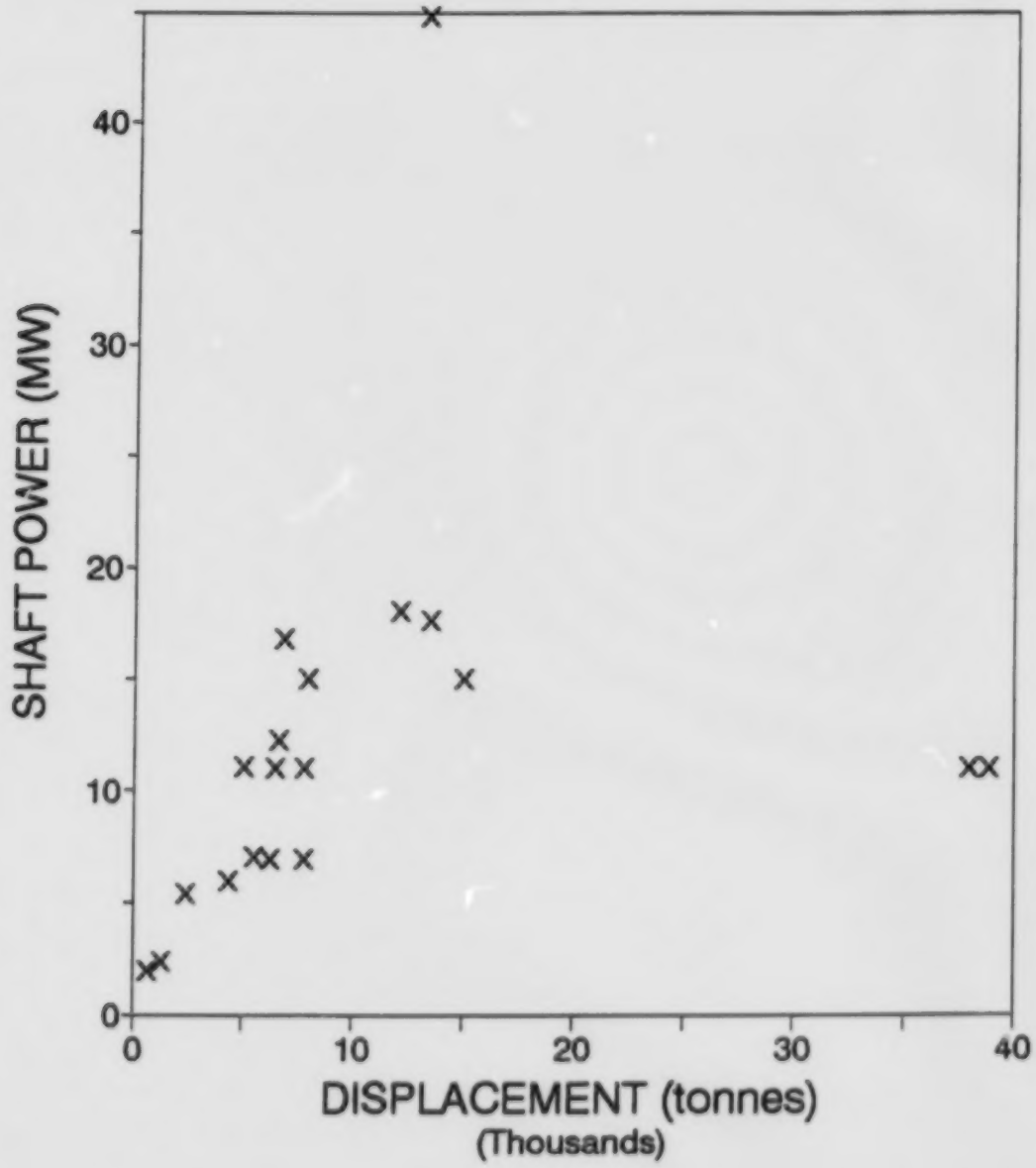


FIGURE 2.3
RANGE OF LENGTH AND PARALLEL MIDBODY

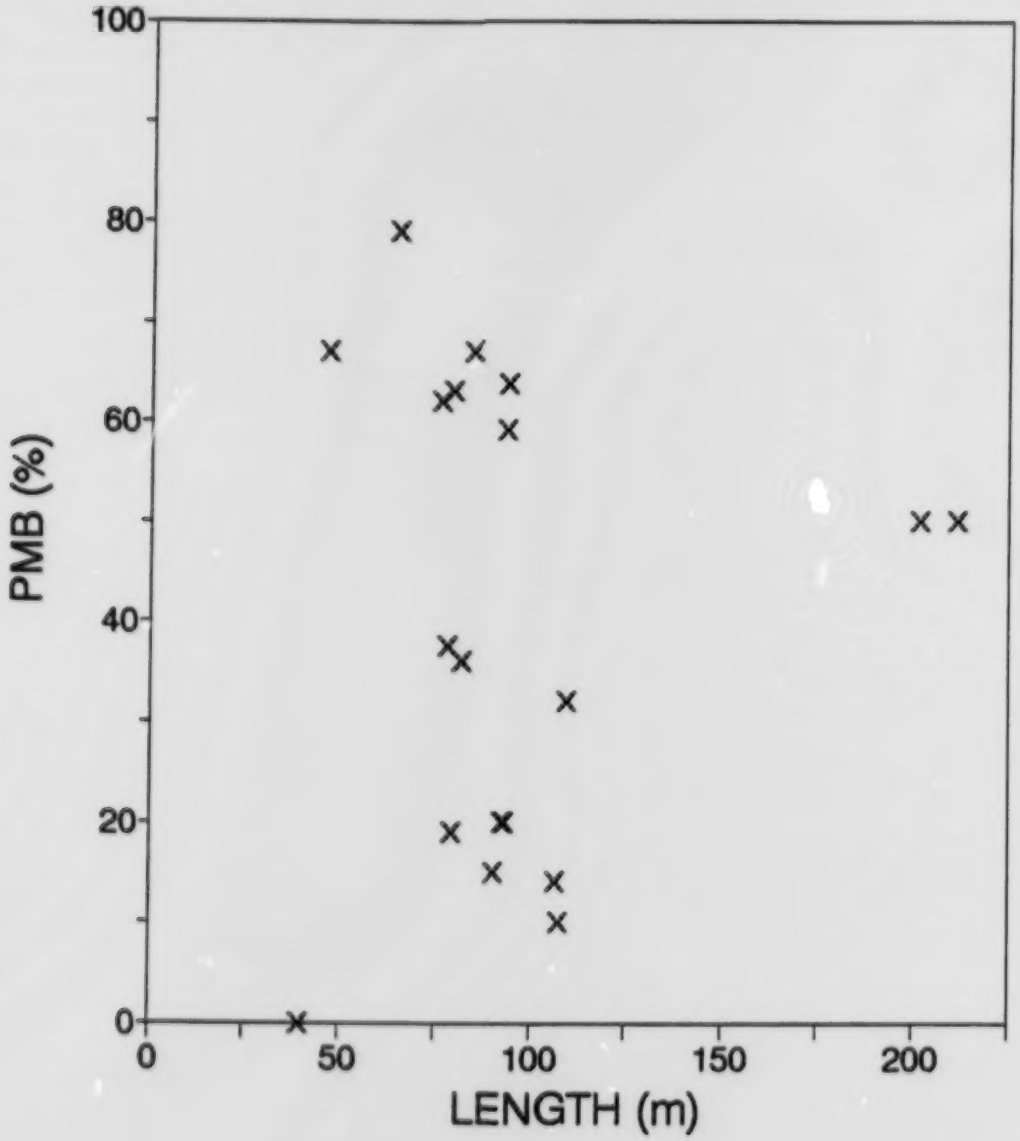


FIGURE 2.4
RANGE OF BUTTOCK AND FLARE ANGLES

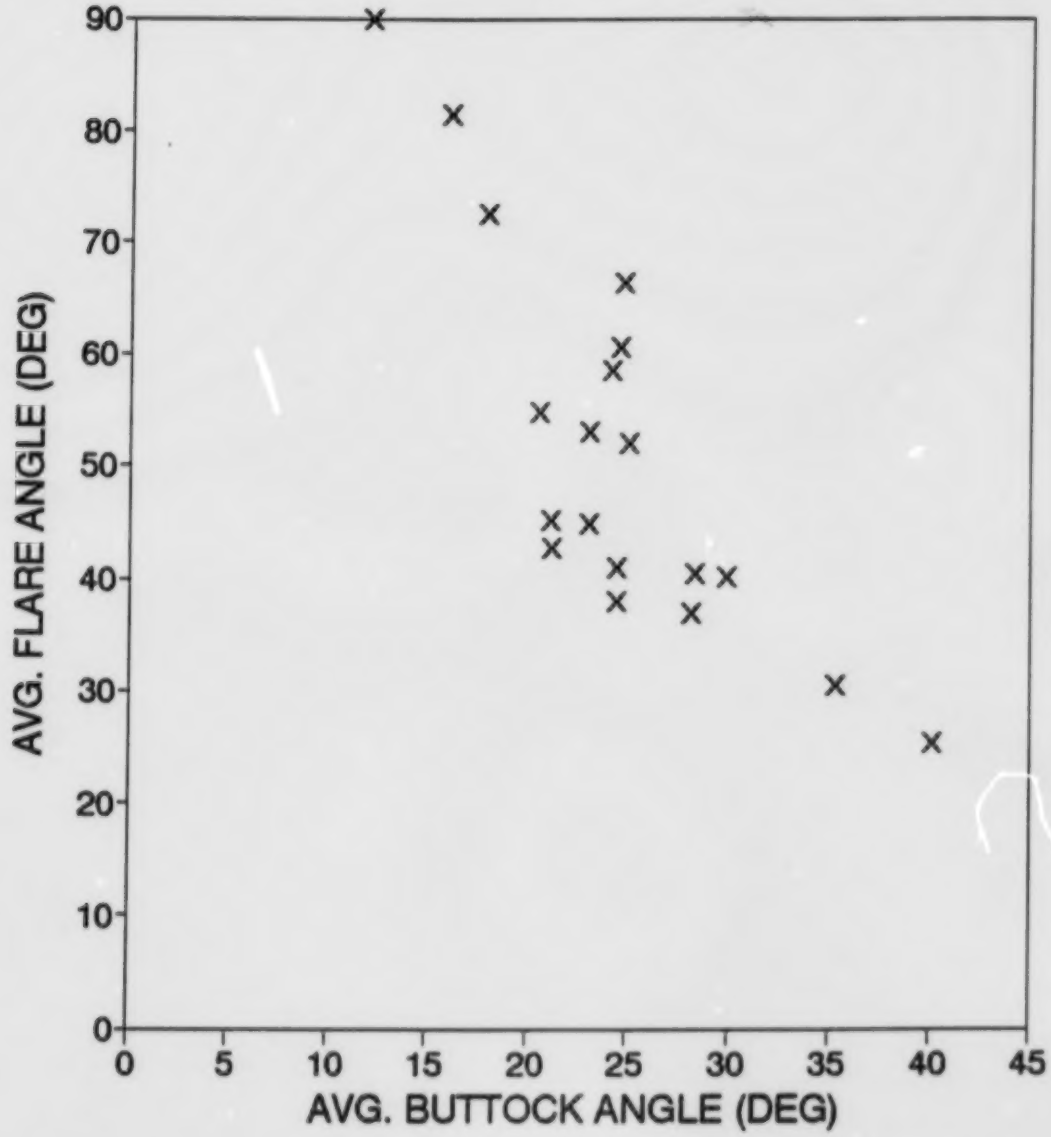


TABLE 2.1
VESSEL DESIGN PARTICULARS

VESSEL	LOA M	LBP M	B-MAX M	DRAFT M	DISPLT TONNES	SHAFT POWER MW	PROPS NO/TYPE	NOZZLES Y/N	PROP DIA M	RUDDERS NO	BOLLARD PULL TONNES
M.V.ARCTIC-OLD	209.50	196.6	22.90	10.90	38000	11.00	1/CP	Y	5.27	1	158.1
M.V.ARCTIC-NEW	220.80	206.0	22.90	10.90	38500	11.00	1/CP	Y	5.27	1	158.1
POLAR CLASS	121.60	102.9	23.80	8.50	13200	44.80	3/CP	N	4.70	1	457.0
R-CLASS	98.20	87.9	19.40	6.90	7800	11.00	2/FP	N	4.10	1	124.4
H. LARSEN	99.80	-	19.50	7.20	8225	14.00	2/FP	N	4.12	1	128.5
L.S.ST.LAURENT	111.70	101.8	24.40	9.00	13500	17.60	3/FP	N	4.57	1	190.7
J.A. MACDONALD	96.04	88.4	21.34	8.54	9310	11.20	3/FP	N	4.12	1	121.3
POLARSTERN	118.00	102.2	25.00	10.50	15000	15.00	2/CP	Y	4.20	1	188.7
MUDYUG-OLD	88.50	78.5	20.00	6.50	6211	7.00	2/CP	N	4.00	2	81.6
MUDYUG-NEW	111.36	89.8	22.20	6.50	7744	7.00	2/CP	N	4.00	2	81.6
TYPE 1100	83.00	75.0	16.20	5.90	5031	6.00	2/FP	N	3.60	1	69.4
TYPE 1050	69.73	58.8	13.70	5.20	2930	6.59	2/CP	Y	3.10	2	99.0
BAY CLASS	42.70	41.0	11.40	3.70	660	1.90	1/FP	N	2.62	1	22.4
OTSO CLASS	99.00	-	24.20	8.00	7950	15.00	2/FP	N	4.60	2	162.2
ODEN	107.80	-	29.40	8.50	13000	18.00	2/CP	Y	4.50	2	233.7
KIGORIAK	90.00	79.3	19.25	8.50	6616	12.20	1/CP	Y	5.30	1	182.3
R.LEMEUR	82.20	78.0	19.03	5.50	5538	7.06	2/CP	Y	3.00	2	116.8
T.FOX	88.00	75.0	17.45	8.00	6824	16.80	2/CP	N	4.80	1	181.1
IKALUK	78.85	70.0	16.61	7.50	5047	11.10	2/CP	Y	3.75	2	163.0
ARCTIC IVIK	67.40	60.8	14.00	4.27	2375	5.37	2/CP	Y	3.10	2	88.9
MAX WALDECK	55.34	-	13.10	4.00	1295	2.31	1/CP	Y	3.25	1	30.0

TABLE 2.2
TRIALS MATRIX

SHIP	DATE	LOCATION	TRIALS PERFORMED	HULL CONDITION	REPORT REFERENCES
FRANKLIN	80-01	LAKE MELVILLE	L,C,M	BARE STEEL	)
	80-03	LAKE MELVILLE	L,M	BARE STEEL	)
	82-01	LAKE MELVILLE	T	INERTA	)
	82-03	LAKE MELVILLE	R,T	INERTA	)
	83-04	LAKE MELVILLE	T	INERTA	) 39-57
					)
PIERRE RADISSON	78-07,08	BAFFIN BAY	L,M,P	BARE STEEL	)
	79-02	ST. LAWRENCE SAGUENAY RIVER	L,M	BARE STEEL	)
ARCTIC	87-08,09	BENT HORN	T	INERTA	)
	86-05,06	BAFFIN BAY	L,C,P	INERTA	)
		ADMIRALTY INLET			) 10-25
	86-06	STRATHCONA SOUND	L,C,M,P	INERTA	)
	80-10	LANCASTER SOUND	L,M,P	INERTA	)
		STRATHCONA SOUND			)
	81-02,03	LAKE MELVILLE	L,M	INERTA	) 1-17
	81-07	ADMIRALTY INLET	R,P	INERTA	)
	82-06	ADMIRALTY INLET	R	INERTA	)
POLARSTERN	84-05,06	HEBRON FJORD	L,C,M,R	INERTA	) 67-69
POLAR SEA/STAR	84-01	MCMURDO SOUND	L	INERTA	)
	82-04	BERING SEA SOUTH	L,R	INERTA	) 26-38
		BERING SEA NORTH		INERTA	)
	85-01	MCMURDO SOUND	M	INERTA	)
L S ST. LAURENT	79-07	STRATHCONA SOUND	L,C,R	INERTA (WATERLINE ONLY)	) 58-65
OTSO/KONTIO	86-03	BALTIC SEA	L,C,R	INERTA/ STAINLESS STEEL	) 79,80
KATMAI BAY	79-01,02	GREAT LAKES WHITEFISH BAY	L,C,M	INERTA	) 73-77
ODEN	89-03	BALTIC	L,C,M,R	INERTA	) 81,82
MUDYUG	87-04	SPITSBERGEN	L,M	INERTA	) 70
MOBILE BAY	86-02	LAKE MICHIGAN	L	INERTA	) 78
ANN HARVEY	89-03	NORTH COAST NEWFOUNDLAND	L,C,M	INERTA	) 71
SAMUEL RISLEY	88-02	THUNDER BAY	M,P	N/A	) 72

L - LEVEL ICE
C - CHANNEL
R - RIDGES/RAMMING
M - MANOEUVRING
T - TRANSIT
P - PROPULSION/ICE INTERACTION

NOTE: OPEN WATER POWER VERSUS SPEED HAS BEEN CONDUCTED FOR ALL VESSELS

TABLE 2.3
VESSEL TRIALS PARAMETERS

VESSEL	LWL M	BEAM-WL M	DRAFT M	DISPLT TONNES	BLOCK COEFF	PMB PER CENT	AVE BUTT ANGLE	AVE FLARE ANGLE	SIDE SLOPE	LWL/B	REAMER WIDTH M
M.V.ARCTIC-OLD	201.80	22.86	10.90	38000	0.71	50.0	35.3	30.5	0	8.83	0
M.V.ARCTIC-NEW	211.90	22.86	11.00	38900	0.71	50.0	20.5	54.8	0	9.27	0
POLAR CLASS	107.30	23.41	8.23	13190	0.62	10.0	21.0	45.2	12	4.58	0
FRANKLIN	93.00	19.34	6.78	7750	0.62	20.0	28.1	37.0	5	4.81	0
RADISSON	92.20	19.22	6.08	6450	0.62	20.0	28.3	40.5	5	4.80	0
L.S.ST.LAURENT	106.30	24.40	9.00	13500	0.56	14.0	40.1	25.4	6	4.36	0
POLARSTERN	109.00	24.00	10.50	15000	0.53	32.0	23.0	45.0	8	4.54	0
MUDYUG-OLD	79.00	20.00	6.50	6211	0.59	19.0	24.4	41.0	8	3.95	0
MUDYUG-NEW	93.20	22.20	6.50	7744	0.56	59.0	12.0	90.0	8	4.20	1.1
TYPE 1100	77.90	16.20	5.44	4346	0.62	37.5	29.9	40.2	0	4.81	0
BAY CLASS	39.60	10.40	3.65	660	0.43	0.0	24.4	38.0	20	3.81	0
OTSO CLASS	90.00	23.50	8.00	7950	0.46	15.0	21.1	42.8	10	3.83	0
ODEN	93.65	29.40	8.10	12090	0.53	63.7	24.7	66.4	0	3.19	2.2
KIGORIAK	84.20	19.25	8.50	6616	0.55	67.0	24.1	58.5	0	4.37	1
R.LEMEUR	79.13	19.03	5.50	5538	0.70	63.0	17.8	72.5	0	4.16	0.5
T.FOX	81.40	17.45	8.00	6824	0.63	36.0	23.0	53.0	8	4.66	0
IKALUK	76.20	16.61	7.50	5047	0.53	62.0	25.0	52.0	8	4.59	0
ARCTIC IVIK	64.70	14.00	4.27	2375	0.62	79.0	24.5	60.6	0	4.62	0
MAX WALDECK	46.58	13.10	4.00	1295	0.52	67.0	16.0	81.5	0	3.56	0.77

TABLE 2.4
ENVIRONMENTAL DATA SUMMARY

SHIP	DATE	LOCATION	FLEX INDEX KPA	ICE THK.	SNOW THK M	AIR TEMP DEG. C	WIND VEL. M/S	COMMENTS
FRANKLIN	1980-01-14 TO 23	LAKE MELVILLE(B)	511	0.62 TO 0.70	0.08 TO 0.15	-1.5 TO -5.4	3.3 TO 8.33	
FRANKLIN	1980-03-25	LAKE MELVILLE(B)	260	0.74 TO 0.88	0.48 TO 0.52	-0.2 TO 2.3	1.9 TO 4.4	
PIERRE RADISSON	1978-07-30 TO 08-07	BAFFIN BAY(S)	(150	0.8 TO 1.22	0	>0	N/A	
PIERRE RADISSON	1979-02-15 TO 25	ST. LAWRENCE(S/B) SAGUENAY RIVER(F)	407 TO 524	0.16 TO 0.88	0 TO 0.15	-23 TO -1	0 TO 18	BEAM TESTS ONLY
ARCTIC	1986-05-31 TO 06-04	BAFFIN BAY(S) ADMIRALTY INLET(S)	(150	0.85 TO 1.13	0.15 TO 0.20	0 TO -4	N/A	
ARCTIC	1986-06-08	STRATHCONA SOUND(S)	(307	1.02 TO 1.55	0.15 TO 0.20	0 TO -4	N/A	ICE TESTING DONE PRIOR TO SHIP TESTS
ARCTIC	1980-10-26 TO 31	LANCASTER SOUND(S) STRATHCONA SOUND(S)	304	0.33 TO 0.44	0.005 TO 0.02	(-12	N/A	AIR T BASED ON ICE SURFACE TEMP
ARCTIC	1981-02-27 TO 03-03	LAKE MELVILLE(B)	267	0.58 TO 1.07	0	APPROX. 0	N/A	BEAM TESTS ONLY
POLARSTERN	1984-05-10 TO 06-10	HEBRON FJORD(S)	(150	0.9 TO 1.22	0	-5 TO 5	N/A	REPORTS DON'T CONTAIN GOOD ENVIRONMENTAL DATA
POLAR SEA	1984-01-09 TO 13	MCMURDO SOUND(S)	172	0.94 TO 1.74	0 TO 0.05	-2 TO -9.5	1 TO 8	
POLAR STAR	1982-04-04 TO 14	BERING SEA SOUTH(S) BERING SEA NORTH(S)	(150 261	0.18 TO 0.49 0.30 TO 0.60	0.10 TO 0.12 0.06	1 TO 2 -14 TO -18	8 TO 15 12 TO 15	
LOUIS S ST. LAURENT	1979-07-27 TO 29	STRATHCONA SOUND(S)	(150	0.74 TO 1.36	0	N/A	N/A	
OTSO	1986-03	BALTIC SEA(B)	330 TO 402	0.65 TO 0.80	0.1 TO 0.25	N/A	N/A	METHOD OF CALCULATING STRENGTH NOT KNOWN
KATMAI BAY	1979-01-30 TO 02-10	GREAT LAKES(F) WHITEFISH BAY	648	0.32 TO 0.52	0.04 TO 0.3	-7 TO -23	2.6 TO 7.9	FRESH WATER ICE FLEX INDEX FROM T
ODEN	1989-03-13 TO 03-16	BALTIC(B)	193 TO 406	0.50 TO 0.70	0.15 TO 0.25	1.0	LOW	BEAM TESTS ONLY
HUDYUG	1987-04-19 TO 21	SPITSBERGEN(S)	370 TO 540	0.69 TO 1.32	0.02 TO 0.13	NA	NA	METHOD OF CALCULATING STRENGTH NOT KNOWN
ROBBLE BAY	1986-02-18 TO 25	LAKE NICKISON(F)	453	0.27 TO 0.52	TRACE TO 0.05	0 TO -7	0 TO 12.9	BEAM TESTS 544 KPA FROM T
ANN HARVEY	1989-03-18 TO 21	NORTH COAST(S) NEWFOUNDLAND	153	0.40 TO 0.66	TRACE TO 0.01	-3 TO -7	1 TO 10	

KEY: S - ICE FORMED FROM SALINE WATER
B - ICE FORMED FROM BRACKISH WATER
F - ICE FORMED FROM FRESH WATER
S/B - DEPENDS ON THE LOCATION IN THE ST. LAWRENCE

TABLE 2.4 CONTINUED

ENVIRONMENTAL DATA SUMMARY (BEAUFORT SEA SHIPS PHASE 1 STUDY)

SHIP	DATE	LOCATION	FLEX INDEX KPA	ICE THK. M	SNOW THK M	AIR TEMP DEG. C	WIND VEL.	COMMENTS
KIGORIAK	79-10,80-03	BEAUFORT SEA(S)	436-550	0.65-1.71	0.03-0.09	-23 TO -37	NA	
	80-06	BEAUFORT SEA(S)	150	1.39-1.69	0.02-0.09	0 TO 8	NA	
	81-05	BEAUFORT SEA(S)	NA	1.27-1.37	0.01-0.03	0.00	NA	
	82-11,12	BEAUFORT SEA(S)	444-468	0.66-0.80	0.02-0.05	-22 TO -35	LIGHT	
ROBERT LEMEUR	82-11,12	BEAUFORT SEA(S)	444-468	0.66-0.80	0.02-0.05	-22 TO -35	LIGHT	
	83-06	BEAUFORT SEA(S)	NA	NA	NA	NA	NA	
TERRY FOX	84-01	BEAUFORT SEA(S)	487-655	0.14-1.55	0.01-0.03	-22 TO -32	LIGHT	WINDS 1 TEST 23 M/S
KALVIK	86-08,09	VISCOUNT MELVILLE SOUND(S)	150-400	1.00-2.30	0.02-0.15	-2 TO -4	LIGHT	WIND MAX 13 M/S
IKALUK	84-01	BEAUFORT SEA(S)	487-655	0.44-1.30	0.01-0.09	-14 TO -30	C26	
ARCTIC IVIK	85-10,11	BEAUFORT SEA(S)	NA	0.42	0.05-0.10	-20 TO -25	NA	
MAX WALDECK	81-03	BALTIC SEA(B)	450-500	0.30-0.90	0.10-0.30	NA	NA	
	82-03	BALTIC SEA(B)	300-340	0.59-0.78	0.05	NA	NA	

KEY: S - ICE FORMED FROM SALINE WATER
B - ICE FORMED FROM BRACKISH WATER

TABLE 2.5
COMPARISON OF ICE STRENGTH DATA

SHIP	DATE	LOCATION	WATER	H-ICE M	AIR TEMP DEG C	SIGMA* BEAM KPA	NO.	E MPA	SIGMA* T-S KPA	BRU MPA	COMMENTS
PIERRE RADISSON	1979-02-19	SEPT ILES	SALINE	0.30 TO 0.55	-6 TO -17	404	6				
	1979-02-20	SAGUENAY PORT ALFRED	FRESH	0.63 TO 0.70	-6 TO -16	429	3				
	1979-02-21	SAGUENAY PORT ALFRED	FRESH	0.54 TO 0.59	-3 TO -10	500	5				
	1979-02-22	SAGUENAY PORT ALFRED	FRESH	0.63 TO 0.71	-1 TO -5	477	3				
	1979-02-25	GASPE	SALINE	0.72	-6 TO -10	523	6				
FRANKLIN	1980-01-20	LAKE MELVILLE	BRACKISH	0.62 TO 0.70	-2.0				511	13.7	
	1980-03-25	LAKE MELVILLE	BRACKISH	0.74 TO 0.88	0 TO 2	300	1		260	10.5	
ARCTIC	1981-02-27 TO 03-03	LAKE MELVILLE	BRACKISH	0.58 TO 1.07	APPROX. 0	267	9	2322		8.4	T-S=464 KPA NOT RELIABLE
ARCTIC	1984-10-26 TO 31	LANCASTER SOUND	SALINE	0.33 TO 0.44	(-12	330	3	1320	297		AIR T FROM ICE SURFACE T
		STRATHCONA SOUND	SALINE	0.33 TO 0.44	(-12	410	4	1400	320		FLARE TEST = 0.46 MPA
LOUIS S ST LAURENT	1979-07-27 TO 29	STRATHCONA SOUND	SALINE	0.74 TO 1.36	)0	154	6		(150		
POLARSTERN	1984-05-10 TO 06-10	HEBRON FJORD	SALINE	0.90 TO 1.22	-5 TO 5	253	2		(150		AT BEGINNING OF TESTS
						197	1		(150		AT END OF TESTS
RESOLUTE BAY	1986-02-18 TO 25	LAKE MICHIGAN	FRESH	0.27 TO 0.52	0 TO -7	453	15	5703			FROM ICE T SIGMA F = 544 KPA

* SIGMA BEAM IS FLEXURAL STRENGTH CALCULATED FROM BEAM TESTS
* SIGMA T-S IS FLEXURAL STRENGTH CALCULATED FROM TEMPERATURE/SALINITY PROFILES

TABLE 2.6
RADISSON: ST. LAURENCE ENVIRONMENTAL DATA

RUN NO.	LOCATION	DATE	H-ICE M	H-SNOW M	SIGMA F KPA	AIR T DEG C	V WIND M/S	COMMENTS
1	ST. LAURENCE MATANE	15-02	0.160	0.000		-30 TO -18	13	
14	ST. LAURENCE SEPT ILES	19-02	0.429	0.000	404	-17 TO -7	8 TO 17	
15			0.482	0.000	404			
17	SAGUENAY PORT ALFRED	21-02	0.650	0.072	475	-10 TO -4	3 TO 10	
18			0.615	0.072	475			
19	SAGUENAY PORT ALFRED	22-02	0.708	0.143	475	-5 TO -1	3 TO 9	
20		24-02	0.779	0.120	475	0 TO 4	0 TO 10	
21	ST. LAURENCE GASPE	25-02	0.712	0.000	522	-0 TO -10	0 TO 5	ICE SALINITY
22			0.707	0.000	523			S1=1.0, S2=1.2

NOTES: 404 KPA IS THE AVERAGE OF 6 BEAM TESTS
475 KPA IS THE AVERAGE OF 11 BEAM TESTS
523 KPA IS THE AVERAGE OF 6 BEAM TESTS

WATER AT PORT ALFRED IS NOMINALLY FRESH
WATER AT SEPT ILES, MATANE AND GASPE IS NOMINALLY SALT WATER (ICE IN THESE AREAS MAY HAVE BEEN FORMED UPRIVER IN WATER OF LOWER SALINITY)

3.0 OPERATOR INTERVIEW

3.1 Introduction

The purpose of the questionnaire was to obtain a qualitative evaluation of the effect of a vessel's design features on its performance in a much wider range of performance categories and mission roles than would normally be evaluated from dedicated trials.

Masters of each of the vessels used in the study have accumulated a wealth of experience on the performance of their vessels under a variety of operating conditions. The master's interpretation and evaluation of their vessel's performance greatly extends the knowledge about the complex interplay between the design features and the mix of performance categories encountered while performing assigned mission roles. When designing ships for a specific role, this knowledge is invaluable for choosing features which enhance performance and avoiding those features which detract from the performance.

It was anticipated that the information gathered might be influenced by the operators' preferences for their own ship and the type of operations conducted. The questionnaire was therefore structured to minimize this effect. However, it was not possible to eliminate an operator's preference for a feature, which although making an operators job easier, may not be justified in terms of overall vessel economics. An example of this would be excessive horsepower.

Full details of the development of the questionnaire are given in Appendix B, which also contains a blank copy of the questionnaire.

The primary emphasis in the questionnaire was the operator's evaluation of the vessel's design features and their effects on the performance of the vessel.

The design features considered were:

Bow and stern shapes
Reamers
Propeller arrangement and propeller type
Rudder location
Length of parallel midbody
Sloped versus vertical midships sides
Bow wedge
Auxiliaries (friction reduction)
Propulsion control
Bow thruster
Heeling system
Hull coating

The performance was considered in two areas: performance

categories and missions.

The performance categories tend to mirror the categories of full scale trials and an attempt was made to focus the answers on these categories. In practice, this was difficult as the ships rarely operate in any one ice regime for an extended period. The performance categories were:

Level ice
Ridges
Broken Ice
Manoeuvring
Pressured Ice
Transit
Propulsion System
Open Water

Each vessel was designed to carry out various mission roles. The ships in the study were designed for a mix of missions chosen from the following missions:

Ice Management
Towing
Ice Escort
Supply (Cargo for M.V. Arctic)
Buoy Handling
Search and Rescue (SAR)

The mix of the missions in the design of each of the vessels was different and this is reflected in the ability of the ship to perform a lower priority mission. Each of the ships operates in different locations, which are seasonally dependent. Table 3.1 summarizes the missions in order of priority and gives an overview of the operational locations and associated seasons.

The masters interviewed for this study, along with the ship which they represented are given in table 3.2. A brief description of each of the ships is given in section 2.1, with the vessels' design particulars listed in table 2.1. In addition, table 3.2 gives information on other icebreaking ships with which each master has operating experience. This helps to understand the basis upon which each of the masters evaluated his own ship.

The questionnaires also asked a variety of questions to further the understanding of the vessels capabilities and limitations. These included:

Limits of performance due to environmental and design features.
Ranking of other vessels with which the master was familiar.
Changes to the present vessel to improve the performance.
The importance of sub components of the performance cate-

gory in the evaluation of the vessels' performance (e.g., how important are ahead vs. astern performance in level ice).

The results of these questions are discussed fully in Appendix B and it is not the intent to discuss them further in this section. The emphasis will be placed on the ability to perform the assigned mission role and the evaluation of the design features.

3.2 Role of Design Features on Performance

3.2.1 Introduction

Each vessel's mission may involve operation in a mixed regime of ice conditions. Some conditions such as level ice are rarely met for extended periods. In this section, an attempt is made to simplify the overall operation, by looking at performance categories and design features individually (see Table 3.3). This simplification leads to a better understanding of the role and importance of each of the design features. The following subsections contain an analysis of the role of the design features in the determination of performance in each of the categories, based on the comments given by the masters to the questions in each of the performance categories in the questionnaire (see section 3.0 of Appendix B).

3.2.2 Level Ice

Performance in level ice is the main criteria which is used to judge the performance of different ships. In practice, level ice without ridging is rarely met. However, the level ice performance is an established criteria for evaluating a vessel's overall performance in ice and the following comments show that performance in level ice is more than a matter of just level ice resistance.

Bow Shape:

All of the bow shapes are judged to be effective in level ice in thicknesses ranging from 2 m for the Polar Star and Oden to less than 1 m for the Earl Grey. As shown in Section 4, the bow shapes of the various ships have a marked effect on the resistance in level ice. This difference in performance is not readily discernable from the interviews.

However, comments by several of the masters lead to a better understanding of bow design for level icebreaking. The Louis S. St. Laurent (with Inerta) tends to stick in ice thicknesses greater than her continuous capability (i.e., greater than about 0.9 m). At the deep operating draft of the St. Laurent (9.8 m), the bow sections have very low flare angles, giving high wedging forces. This is typical of the older bow designs including the John A. MacDonald. The Kontio has much higher flare angles than the St. Laurent and is self extracting

(i.e. astern power is not required to free the ship at the end of a ram) in ice thicknesses greater than her continuous capability. The Kontio's master did comment that in ice much thicker the Baltic, the bow would be more effective if it had a larger waterline entrance angle i.e. more like Oden. As the primary role of most of the icebreakers in this study is escort, the condition of the track is important for the following ship. The track of the Polar Star has a high concentration of ice which means much of the ice broken at the bow passes under the ship without being displaced under the surrounding ice cover. (See also comments on propulsion/ice interaction.) The track of the Earl Grey, at low speed, is only as wide as the ship, making it difficult for wider ships to follow. The track of the Oden is clearer and wider than other Baltic icebreakers, although at higher speeds the track is not as clear.

Bow Stopper:

Other than on the Earl Grey and Oden, the effect of the bow stopper on level ice performance is not noticeable. On the Earl Grey, the stopper often traps broken ice, carrying it along with the ship. The stopper on this ship is second largest of any in the study (Oden's wedge/stopper is larger) and is very close to the surface. As will be apparent from comments in the following performance categories the stopper is not well designed. The wedge/stopper on the Oden helps to maintain a clear track as described above and in addition minimizes the amount of propeller/ice interaction (along with other hull features).

Reamer:

The only ship in this study with reamers is the Oden. The main reamers give the bow a beam 4.4 metres wider than the midbody. The reamers reduce the friction along the parallel midbody of the ship by breaking a track wider than the midbody.

Length of Parallel/Shape Midbody:

Four of the masters (Polar Star, St. Laurent, MacDonald and Radisson) commented on the tendency of their ships to wedge at tha shoulders in thicker ice. These ships are characterized by long gradual transitions from the bow to the midbody, with low flare angles (and hence high wedging forces) as the waterline approaches the midbody. The amount of flare close to the midbody varies on the ships depending upon the slope of the midships sides, which ranges from 12 degrees on the Polar Star to 5 degrees on the Pierre Radisson. Although the Henry Larsen has a similar hull form to the Radisson, the use of the bubbler in most ice conditions masks the effect of wedging. The 1100 class have high flare angles at the shoulder but neither master noted wedging as a problem. The Black has operated primarily in broken ice regimes in the Arctic and the Cornwallis in the Gulf of St. Lawrence. Both ships may not have encountered similar ice conditions. The transition on the Arctic (new bow) is rel-

atively short and wedging at the shoulders was not identified as a problem. Neither the Oden (with high flare angles at the shoulder) or the Kontio note wedging as a problem.

Stern Shape:

Only the masters with transom (Martha Black) or square "supply boat" sterns (Earl Grey) commented unfavourably on the astern performance in level ice. The Martha Black is operated in Arctic summer ice with deep stern drafts to minimize propeller/ice interactions. At these drafts, the transom stern (whichis nearly vertical) pushes ice instead of submerging it. The stern of the Cornwallis although similar (but with rounded instead of knuckled corners) does not have the same problem operating in thinner Gulf of St. Lawrence ice. The stern of the Earl Grey pushes against the ice but is not effective in breaking it. The stern of the Oden, although wide, has good icebreaking angles and performs satisfactorily astern in level ice. The stern of the Kontio is very fine which causes squatting in shallow water at high powers and is undercut at the aft end which causes poor astern directional control and manoeuvrability. It does however break ice effectively. The sterns of the larger icebreakers both break ice and push it aside and down.

Propeller Arrangement:

With the exception of the Earl Grey, Arctic and Oden which are fitted with nozzles, all of the ships have open propellers. The common problem is the amount of propeller/ice interaction, particularly astern. The ships with deep propeller submergence, St. Laurent and MacDonald, have minimal interaction in ahead icebreaking. The Radisson which is designed to operate at two drafts has increased interaction at the lighter draft. The stern shape of the Polar Star, coupled with the exposure of the wing screws causes interaction ahead and astern in the thick ice in which the ship operates, despite the deep propeller immersion. The interaction astern is severe enough that very little astern icebreaking is carried out in level ice. Despite the deep draft on the Arctic, propeller/ice interaction occurs astern because of the narrow stern and steep stern sections (which offer little protection) coupled with the suction of the nozzled propeller. The ice which accumulates behind the Earl Grey's square stern is sucked down by the nozzled propellers. The propellers on the Martha Black are very exposed and hence susceptible to interaction, which can be very severe even in level Arctic ice. In shallow water the propellers of the Cornwallis are considered too close to the bottom and affect the manoeuvrability. The amount of propeller/ice interaction on the Oden is minimized by the submergence of the propellers and their proximity to the centreline. The Kontio/Otso are the first major Finnish icebreakers without twin bow propellers and their manoeuvrability astern is poor in comparison to their predecessors.

Propeller Type:

The propellers on the Martha Black are too weak for the extreme conditions in which she is expected to operate as 5 breakages have occurred in two years. The reluctance to break level ice astern on the Polar Star suggests that the Polar class icebreaker propellers (as well as the shaft thrust foundations) are not strong enough for the vessels to achieve their full icebreaking potential. The increased thrust from the nozzled propellers on the Oden enhances the icebreaking in thick ice at slow speeds. In shallow water, they tend to pick up bottom debris and cause the stern to squat.

Rudders:

Damage to the rudder(s) is not a major concern in level ice for these vessels. On the St. Laurent the rudder horn offers little protection to the rudder as it does not overlap the trailing edge. However the trailing edge is deeply immersed (about 3 m). The hull on the Arctic offers little protection to the rudder although the rudder horn effectively protects the trailing edge. Because of the limited strength of the rudder stock and the steering gear caution is exercised when backing to minimize the loadings on the steering system.

Propulsion Control:

The full ahead/full astern time is of concern on the Arctic and the Martha Black. The Arctic spends considerable time ramming level ice beyond its continuous capability during the first run into Nanisivik each season. With the slow response time of about 40 s, the master must anticipate events. To minimize the risk of damage, the tendency is to err on the conservative side which reduces the efficiency. On the Martha Black, the slow response time (14 to 20 seconds) increases the risk of damage to the propellers, as it is more difficult to avoid multi-year ice interaction due to the increased reaction time required. The full ahead/full astern time of the Cornwallis (the other 1100 class) is about 11 seconds which is fast enough.

Bow Thrusters:

None of the masters use the conventional thrusters in level ice. The bubbler on the Larsen is used to enhance manoeuvrability.

Friction Reduction Auxiliaries:

The Arctic, Larsen and Kontio are fitted with bubbler systems and the Oden is fitted with a water wash system. When working, the Arctic's system has proven useful in high friction conditions in thick ice. Because of its unreliability it has been used infrequently and recently the bow air openings have been sealed off. The Larsen's system is used in virtually all

conditions. On the Kontio the system is used only in thick ice with snow, and in addition to friction reduction it reduces the amount of propeller/ice interaction. The water wash system on the Oden is used in high friction conditions, particularly in thick Arctic ice with snow.

Heeling System:

Active systems are fitted to the Polar Star, St. Laurent, MacDonald, Radisson, Larsen, Oden and Kontio. The systems on the Polar Star, Kontio and Oden are used in level ice in high friction conditions. The other systems are not used. The passive flume system of the Martha Black is left at working level in level ice as the rolling induced by the transfer of liquid seems to assist the icebreaking.

Hull Coating:

Several of the ships (St. Laurent, MacDonald and Radisson) were coated with Inerta after they originally went into service. The difference in performance was noticeable and the masters consider it essential for efficient icebreaking. On the Kontio the stainless steel band at the waterline is very effective in reducing friction.

3.2.3 Ridges

Effective and efficient performance in ridges is the major determinant in the average speed of a vessel transiting a mixed ice regime which includes significant ridging. Assuming multiple rams for full ridge penetration, a ram cycle in ridges is composed of four distinct phases;

1) acceleration in channel
2) impact and penetration
3) extraction
4) backing in channel

Deficiencies in performance in any phase can add considerably to the ram cycle time and reduce transit speed. The following sub-sections describe the importance of the vessel design features in the determination of good ridge performance.

Bow Shape:

It is not possible from the interview to quantify the effects of bow shape on ridge penetration due to the many variables for both the ships in this study and the characteristics of the ridge. The variables for the ships include bow profiles and section shapes, displacement, power and impact speed. The variables for the ridge include ridge depth, degree of consolidation, ice strength, snow cover, etc. Quantification of ridge performance can only be done under controlled conditions with known ridge properties.

However, certain bow characteristics do contribute to effective ridge performance. The masters commented on three aspects of ridge performance; tendency to get stuck, bow shape for effective ridge penetration and lack of directional stability.

The newer generation bows such as Polar Star, Pierre Radisson (first year ice only), Henry Larsen, Earl Grey and Edward Cornwallis (experience limited to first year ice only), Oden and Kontio perform well in ridges. The older generation bows (St. Laurent and MacDonald) with small flare angles and hence high wedging forces (particularly at the shoulders) become stuck in thicker ridges requiring multiple rams. The Arctic gets stuck in ridges in late winter when the cold temperatures and the snow cover produce high friction conditions. As these ridges are large enough to require multiple rams, the shoulder region once immersed in the ridge produces high wedging forces. The small power to displacement ratio and the length of the parallel midbody contribute to the difficulty in extraction.

Ridges are broken by using the downward forces generated at the bow as the bow is lifted onto the ice. On the Martha Black, the bow stopper effectively stops the ship before the bow has lifted to any significant degree. In Gulf operations, the Cornwallis experiences greater difficulty in breaking through grounded ridges, suggesting that the stopper interferes with progress. On the Radisson the stem angle increases with depth. This is thought to act much as a stopper preventing the bow from rising as far as it would with one angle throughout.

The very low flare angles throughout the length of the MacDonald's bow cause high lateral forces when the ship strikes an ice feature unsymmetrically. The ship is therefore easily deflected from her course, making it difficult to hit an intended target when the approach is in an uneven channel. As the St. Laurent has similar angles in the bow, it is believed that she would exhibit similar tendencies.

With multi-year ice present the strength of the bow becomes a factor in ridge ramming. The risk of damage will increase the caution of the operator resulting in reduced impact speeds and hence reduced penetrations. This is especially relevant for the ridge performance of the Martha Black, which has a weak bow.

Bow Stopper:

The stoppers on these ships were designed to stop the ships before beaching when ramming aggressively. The MacDonald and Kontio are not fitted with stoppers. With the exception of the Martha Black and Oden, the stoppers don't engage or rarely engage (Radisson only). The stopper on the Martha Black is close to the waterline, preventing the ship from achieving any

significant ridge penetration. In addition the stopper is blunt and close to vertical bringing the ship to an abrupt halt with high decelerations. The stopper on the Oden is thought to increase the resistance in ridges. Of the four Canadian/American major icebreakers with stoppers, the R class's is by far the most pronounced and the closest to the waterline, making it the most likely to engage a ridge. In Arctic service the stopper of the Radisson rarely contacts the ridge. With limited Arctic service and more conservative operating procedures, the Larsen's stopper has not contacted the ridge.

Reamers:

Because of the increased beam over the main reamers, the Oden has higher initial resistance in the ridge, but reduced midbody friction. This increased beam also increase the resistance when backing out of a ridge, but contributes to a cleaner channel astern which helps to reduce the backing resistance in the channel. In ridges with high sails, the upper turning reamers (which give a beam 1.6 m wider than the main reamers) contact the ice and increase the resistance.

Length of Parallel/Shape of Midbody:

Four of the masters mentioned the tendency to stick at the shoulders (Polar Star, St. Laurent, MacDonald and Radisson). These vessels are operated more aggressively in larger ridges than the smaller icebreakers and hence would be more likely to become stuck. These ships have long transitions from the bows to the midbodies with low flare angles and hence high wedging forces. Although the Larsen is similar to the Radisson, the use of the bubbler may mask the effects of wedging.

The lengths of the parallel midbodies on the Arctic and the Martha Black restrict the manoeuvrability in ridges. This lack of manoeuvrability can prevent the ship from attacking a ridge at the easiest point or widening a hole through a ridge to prevent the ship from becoming stuck in a ridge requiring multiple rams.

Sloped versus Vertical Sides:

The Polar Star has the highest side slope (12 degrees) of the ships in this study. This is thought to assist the ship in extraction from a ridge. Conversely the 10 degree slope on the Kontio is thought to cause wedging. The larger beam and much smaller displacement of the Kontio may help to explain this difference. On other ships with lesser slopes (5 and 6 degrees) or vertical sides, this factor was not considered to have any effect. The vertical sides of the Oden are effective in ridges when the heeling system is used to "duck walk" the ship.

Stern Shape:

As in level ice performance, the key issue is performance astern. With the exception of the ships with the square or transom sterns, the ships have effective sterns for going astern in the broken ice in the ridge approach channel. The ships with effective sterns have stern shapes which are similar to those found at the bows i.e., similar flare angles and waterline shapes. At deep drafts, the transom stern of the Martha Black pushes ice astern, and the accumulation of ice astern hinders astern motion. The propellers are exposed as the stern offers little protection. The Earl Grey rarely needs to go astern in the ridges which she encounters in the Gulf of St. Lawrence, and hence the poor astern performance of the supply boat stern in high concentrations is rarely an operational problem. The proximity of the Oden's rudder stops/ice knives to the waterline reduces the performance astern as the ice, which is pushed down by the hull, contacts these features and accumulates astern. Squat in shallow water is again an operational concern on the Kontio.

Propeller Arrangement:

The operational concerns are propeller/ice interaction and risk of damage. The seven major icebreakers have good propeller immersion and hence in moderate ridges have little interaction. In more severe ridging (extending to the keel depth or beyond), with multi-year ice present, their is universal concern about damage (particularly on the open screw ships), especially astern. To avoid ingesting ice (and hence minimizing the risk of blockage) at the start of the acceleration run of a ram, the masters of the Arctic and Oden only use partial power until the ship is underway. This avoids sucking the ice, which has accumulated astern when backing, into the propeller/nozzle. The Martha Black suffers a lot of propeller/ice interaction as the hull does not protect the propellers and the propellers are not deeply immersed relative to the ice thicknesses in which she operates. The nozzled propellers on the Earl Grey are rarely blocked. This is the result of the operational profile rather than the design, as the ship rarely has to back in the ridges in which she operates.

For those ships with multiple screws, the masters can use the differential thrust to manoeuvre astern for setting up the next ram or to twist the ship for extraction from the ridge. With the twin screw ships in thick ice this possibility may disappear as the full astern thrust of both propellers may be required to maintain astern way.

The nozzled propellers on the Oden increase the thrust significantly, which increases the acceleration and reduces the distance the ship needs to back to achieve a given impact speed.

Propeller Type:

For those ships with fixed pitch propellers, the masters are concerned about the risk of damage, particularly astern, in the presence of multi-year ice. This suggests that the requirement to reverse the direction of the propeller exposes the propeller to a higher risk of damage when the propeller is stopped and the ship is still underway. The fixed pitch propellers on the Kontio suffer little thrust degradation in thick ridges.

Rudders:

In general the rudders are not a concern in ridge operation. As described earlier, the lack of hull protection and the relatively weak steering gear system on the Arctic limit the astern capability because of the risk of high loadings with resulting damage. In thick ice and heavy ridging the master of the Kontio operates cautiously astern as he is concerned about damage. The single centreline rudder on the twin screw Larsen limits the ability to manoeuvre at slow speeds.

Propulsion Control:

The time to reach full astern power from full ahead power (or vice versa) is the major operational concern. If the time is long, the master must anticipate events such as ridge or thick level ice extraction and the avoidance of propeller interaction with multi-year ice. The tendency is to err on the conservative side. This coupled with the length of time to change the thrust direction increases the ram cycle time. Both the Arctic with 40 seconds and the Martha Black with 14 to 20 seconds are considered too slow. The Polar Star with about 40 seconds is not considered too slow. With the high power to displacement ratio of this vessel, the importance of the ahead/astern time may be diminished.

Bow/Stern Thrusters:

With the exception of the bubbler on the Larsen, not used in ridges.

Auxiliaries for Friction Reduction:

When working the bubbler on the Arctic has proven useful in ridges to avoid sticking. However low reliability precludes its use. The bubbler on the Kontio is used in conjunction with the heeling system to reduce wedging in heavy ridging. In lighter ridging it is not used due to the high power consumption. The bubbler on the Larsen is used in all ridging to reduce friction and ease extraction. In addition it helps to clear the path ahead of the ship when going astern, thus easing the forward motion on the next ram. The water wash on the Oden is used to lubricate the ice ahead of the ship to reduce friction and aid extraction.

Heeling Systems:

On the Radisson and the Polar Star, the heeling systems are able to transfer a large volume of water in a short time period (about two minutes) and hence are effective for extraction. The system is not used on the Larsen. On the MacDonald the transfer time is about 10 minutes which is too slow to be effective. The system on the St. Laurent is not working. The systems on the Oden and the Kontio are used in the automatic cycling mode to increase the effectiveness in ridge penetration.

Hull Coating:

A good low friction coating or surface (stainless steel on the Kontio) is essential for effective ridge operation, especially for extraction. The coating of the St. Laurent's hull with Inerta has dramatically reduced the extraction time in ridges. The hull coating on the Larsen has deteriorated (about 40% gone), and the master is noting decreased ridge performance.

3.2.4 Broken Ice

Broken ice is encountered when the ship has to negotiate a previously broken channel or navigate through an area of ice broken by wind and current. The ice may be consolidated. The extent of consolidation will depend upon the temperature and length of time since the ice was broken. In addition, in the Arctic or in eastern Canadian operations old or multi-year ice may be mixed in with first year ice posing a threat to both hull and propulsion system.

Because of the extreme variability of the broken ice conditions, quantification of performance in the regime is difficult unless trials are conducted under controlled (vessel speed and power) and measured (ice size pieces, degree of consolidation, etc.) conditions. Nevertheless, operations in broken are important as many of the missions (such as escort in the Gulf of St. Lawrence and Baltic) are carried out predominantly in this regime.

The following sub-sections indicate the role of various design features in the determination of good broken ice performance.

Bow Shape:

In channels, all the bows perform satisfactorily. The bow of the St. Laurent tends to push ice ahead of it, due to the near vertical bow at drafts greater than 9.1 m. The bow of the Oden has a predominantly downward force which eliminates wedging.

In rubble, the bows of the R class and the MacDonald tend to bounce off the larger and stronger floes, making it difficult to maintain a straight course. The low flare angles along the length of the MacDonald's bow give high lateral forces when impacting a floe unsymmetrically. The flare angles of the Radisson are higher in the immediate area of the bow but are similar to those of the MacDonald further aft in way of the shoulder. As this is the area most likely to contact the floe, the Radisson also is difficult to keep on course in rubble conditions. This is compounded on the Radisson by the slow response to a helm order (see below). As the St. Laurent has similar angles to the MacDonald, she is likely to exhibit similar tendencies.

The quality of the track when escorting is an issue with three of the masters. The Polar Star leaves a lot of ice in the track, making it difficult for escorted vessels to follow. The track of the Earl Grey is only as wide as the ship at low speeds, making it difficult for wider ships to follow. Although the track of the Kontio is clearer than the earlier generation Finnish icebreakers the master would like less ice in the track.

Bow Stopper:

With the exception of the 1100 class and the Oden, the bow stopper on these ships has no discernable effect in broken ice. On the Black, the stopper tends to collect large floes which are pushed by the ship. When they release they often end up in the propellers. On the Cornwallis, the bow does not push the thinner Gulf ice, but the steepness of the stopper brings the ship to an abrupt halt. The stopper/wedge on the Oden helps to maintain a clear track by pushing ice to the side.

Reamers:

As in previous performance categories, the reamers reduce the friction along the midbody.

Length of Parallel/Shape Mid-Body:

Ice may hang up on the shoulders of the Radisson due to the low flare angles. Although not mentioned by the masters of the St. Laurent, the MacDonald and the Larsen, the presence of similar angles at the shoulders should give rise to similar tendencies. The use of the bubbler on the Larsen tends to mask any detrimental effects of wedging. The lengths of the parallel midbodies of the Martha Black (and to some extent on the Cornwallis operating in Gulf ice) and the Arctic, restrict the manoeuvrability in high ice concentrations. Although the midbody length of the Earl Grey is considerable, it is believed that the high power allows the ship to proceed in most broken ice conditions at speeds that create a large bow wave which breaks up the ice along the length of the ship allowing it to turn. At lower speeds, the ship would be expected to have

restricted manoeuvrability due to the length of the midbody.

In general all the icebreakers have large wakes at high speed which breaks the ice well beyond the beam of the ship. This is useful for escorting ships wider than the icebreaker and improves the manoeuvrability of the icebreaker.

Stern Shape:

The ships with good icebreaking sterns have few problems in broken ice when going astern. Transom (Black) and supply boat (Grey) sterns tend to push ice which accumulates, eventually stopping the ship. In Gulf operations on the Cornwallis, this is not a problem although the master feels that the top of the rudder is not well protected by the stern. The stern of the Kontio squats in shallow water, but in conjunction with the rise of floor midships keeps ice out of the wake. The stern of the Oden tends to accumulate ice on the ice knives/rudder stops. The stern of the Polar Star tends to upend floes.

Propeller Arrangement:

Two of the masters commented on the contribution of the multiple screw arrangement to course control through the use of differential thrust. These were the triple screw Polar Star and the twin screw Pierre Radisson. On the Radisson, using the propellers to steer compensates for the slow response of the ship to a helm order as the single centreline rudder is not in the wake of the propellers. The master of the Larsen commented that in thick ice, it is not possible to manoeuvre the ship when going astern as all the thrust is required to maintain stern way

The weakness of the propellers of the Martha Black was again cited by the master. This was not cited as a major problem for the Gulf operations of the Cornwallis, although she has damaged a blade when operating in the Strait of Belle Isle. All masters (particularly those operating the open screw ships) exercise caution when operating in old ice.

The nozzled propeller on the Oden increases the thrust which enhances the performance in rubble, although the performance may be degraded by blockage in thick ice.

Rudder:

As described above, the single centreline rudder of the twin screw Radisson, exacerbates the tendency of the ship to steer an erratic course when she bounces off a floe. As the rudder is not in the wake of the propellers, it requires large angles of helm before it becomes effective, or is slow to respond due to the small lifting force caused by the low velocity of the wake. Similar problems were mentioned by the masters of the Black and the Larsen.

Propulsion Control:

The fast response time and the ability to control the propellers individually contribute to the course keeping of the Radisson described above. On the Martha Black, the slow ahead/astern time compromises the slow speed manoeuvring using differential thrust.

Bow Thruster:

The bow thruster is used on the Martha Black to assist in open water leads to compensate for the slow helm and thrust response. See below for the Arctic.

Auxiliaries for Friction Reduction:

The air bubbler on the Arctic has not proven to be reliable. When operational, it was used in the bow thruster mode for manoeuvring and also to reduce friction in "deep porridge" when operating in the bubbler mode. On both the Larsen and the Kontio, the bubblers widen the channel astern and reduce the amount of propeller/ice interaction. The water wash system on the Oden is used to reduce the friction in old channels.

Heeling System:

The passive flume system on the Martha Black is kept at operating level as it assist the passage through broken ice by inducing a roll as the ship manoeuvres. The system on the Oden is used in the cycling mode (but limited to 2 to 3 degrees) to assist passage in old channels.

Hull Coating:

All the masters thought a good low friction coating or surface is essential to minimize friction.

3.2.5 Manoeuvring

Manoeuvring in ice is divided into the following components:

- turning ahead
- turning astern
- channel breakout ahead and astern
- Captain's/star manoeuvre

Manoeuvrability is a vital component of successful ship escort and ice management. Good manoeuvrability is also a prerequisite for fast transit as it enables the ship to avoid large ridges and other ice features which would reduce the

average speed.

The discussion in the following sub-sections provides details of the role of the design features in providing good manoeuvrability.

Bow Shape:

In general, the role of the bow in manoeuvring ahead is not quantifiable from observations aboard the ships. The masters of both the Oden and the Kontio commented favourably on the role of the bow in offering good manoeuvrability. On the Martha Black, the shape of the bow (including the bow stopper described below) is thought to hinder the manoeuvrability.

The ahead component of the star manoeuvre, and channel breakout involve similar considerations, i.e., the ability to break into unbroken ice from a broken channel. Of those ships with a short parallel midbody (Polar Star, St. Laurent, MacDonald, Kontio and 'R' class), those ships with the least amount of flare along the length of the bow (St. Laurent and MacDonald) have the greatest amount of difficulty in channel breakout. On the Radisson, the flare decreases with increasing draft and hence the ship has more difficulty in channel breakout at the deeper operating drafts. Although the master of the Larsen rates the ship as good in channel breakout, she does tend to bounce off stronger ice and follow leads which shows that the lower flare angles in the shoulder region give high lateral forces. The bow of the Oden has very high flare angles to the full beam of the ship and breaks out of a channel easily.

Bow Stopper:

On the Martha Black, the bow stopper is large and located close to the waterline. Ice tends to hang up on it during a turn, which hinders manoeuvring. This only appears to be a problem in the Arctic operations of the 1100 class.

Reamers:

The main reamer of the Oden (in conjunction with the narrow stern and heeling) permit the ship to make small turns in ice despite the significant length of parallel midbody.

Length of Parallel Mid-Body

The lack of manoeuvrability in high ice concentrations is dominated by the lengths of the parallel midbodies on the Arctic and Earl Grey. On the 1100 class, the midbody length is also a major factor. The midbody lengths in ascending order are; 1100 class, Grey and Arctic. (See above for Oden.)

Sloped Midship Sides:

Sloped sides are thought to assist manoeuvring by breaking and displacing the ice. The maximum slope of the ships in the interview process was on the Polar Star with 12 degrees. Only the master of the Kontio (with 12 degrees) thought this feature enhanced manoeuvrability.

Stern Shape:

The square stern of the Earl Grey prevents manoeuvring astern in high ice concentrations of virtually any ice thickness as it accumulates ice behind the ship, preventing movement. At deep drafts the transom stern of the Martha Black behaves similarly, but not to as great an extent. Although this was not a factor for Gulf operations, the master of the Cornwallis does not manoeuvre astern. The stern of the Kontio is poor for astern directional control as it tends to follow the path of least resistance. The stern of the Oden accumulates ice when going astern which restricts manoeuvring. As the stern of the Oden is narrower than the midbody, the ship has room to swing when manoeuvring. The other ships have good astern manoeuvrability as their sterns break ice and push it aside. The Arctic does not manoeuvre astern due to the vulnerability of the steering gear and the single propeller which offers no differential thrust capability. Particularly in thick ice, the Polar star minimizes the amount of astern manoeuvring due to the risk of damage to the propellers.

Propeller Arrangement:

The ships with multiple screws (all except Arctic) use differential thrust to manoeuvre the vessels astern when the rudders are centred to prevent rudder damage. Differential thrust is also used in channel breakout manoeuvres and for manoeuvring ahead for those ships with slow helm response. In thicker ice, when higher powers are required to maintain stern way, the twin screw ships become unmanoeuvrable as any use of differential thrust reduces the stern thrust and the ship loses way. This is particularly evident to the master of the Kontio as he was used to the good manoeuvrability of the earlier ships with twin bow and stern propellers. Similarly the masters of the Larsen and Cornwallis (with twin screws) have had operational experience on the MacDonald (a triple screw ship) and compare their ships unfavourably with the MacDonald when manoeuvring astern. The closeness of the propellers of the Oden to the centreline reduces the effects of differential thrust. On the other hand if required to manoeuvre astern on one propeller, the ship is easier to handle. When using differential thrust and high powers the Kontio has significant vibration.

As the outboard propellers of the Polar Star can have enough propeller/ice interaction in a turn to stop the shaft, the helm angle is restricted in heavy ice. The vulnerability of

the propellers of the Radisson in thick ice require operator caution when turning astern to avoid damage. As the propellers of the Martha Black are not well protected by the hull, the risk of damage increase significantly when performing any manoeuvre. Although not a major concern in Gulf operations, care is taken by the master of the Cornwallis to minimize propeller/ice interaction. The propellers of the Oden are well protected by the Nozzles when manoeuvring.

Propeller Type:

No comments were made to differentiate between those ships with fixed pitch and controllable pitch propellers. On the Radisson, changing thrust direction when the ship is moving exposes the propeller to a higher risk of damage as the propeller stops rotating. This tends to occur more frequently on the Radisson as the differential thrust is used to compensate for the partially effective rudder. The propeller of the Martha Black is too weak for operation in thick ice, particularly multi-year ice. The nozzles of the Oden concentrate the wake on the rudders providing high lift and immediate response.

Rudders:

The major concern is the length of time for the ship to respond to the helm. The single rudder ships with twin propellers (Radisson, Larsen, Cornwallis and Black) are slow to respond to a helm order (about 15,8,6 and 6 seconds respectively). This increases the overall manoeuvring time and may increase the risk of damage to hull, propellers and rudder if a fast manoeuvre is required. On the Arctic, the hard over to hard over time is about 40 seconds which is too slow for efficient manoeuvring. The rudders on the Arctic and Cornwallis are susceptible to damage, which reduces the astern capability.

Propulsion Control:

As described above the outboard propeller can be stopped in a turn on the Polar Star. In this event the gas turbines can take about 15 to 20 minutes to get back on line. Aggressive manoeuvring in thick ice is therefore avoided as it can be counter-productive. The ahead/astern times on the Arctic, the Black and the Kontio are slow (40, 20 and 20 seconds respectively). As the master must anticipate events, the tendency is to err on the cautious side to avoid damage. This increases the manoeuvring time or increases the risk of damage for an event requiring fast response. On the Oden the master is able to perform Star manoeuvres quickly as the ahead/astern time is 6 seconds.

Bow Thrusters:

The conventional thrusters are not used in ice. Although the bubbler on the Arctic would be used as a thruster or for friction reduction to increase speed, the lack of reliability

precludes its use. The Larsen's bubbler is used in thin ice at slow speeds. When manoeuvring close to piers or other ships it acts as cushion. The Kontio's bubbler is not considered efficient for manoeuvring in ice and is only used when going astern to enhance manoeuvrability.

Friction Reduction Auxiliaries:

As they reduce the friction in high friction conditions the speed of the vessel is increased. At the higher speeds the vessels manoeuvre better.

Heeling System:

The system on the Oden is used as it has a fast operating time. In baltic operations, a heeling angle of 2 to 3 degrees is sufficient to significantly reduce the turning diameter. the turning reamers require an angle of 7 degrees to contact the ice. To the date of the interview, use of this angle has not been necessary. It may be necessary in thick ice, but at this angle crew comfort and ship's operation start to become an issue.

Not used for turning with on the other ships with a fast heeling system as the masters were not aware of any advantages. Although the master of the Arctic is aware of the significant reduction in the turning circle with heel, the speed of ballast transfer is too slow to be of practical use.

Hull Coating:

In general, thought to be a necessity for effective manoeuvring as it reduces the friction and keeps the speed up for tighter turns.

3.2.6 Pressure Ice

This is the most difficult performance category to deal with as the degree to which the ice is pressured has, to date, only been inferred from observations. These observations include:

- how quickly the track closes
- wind speed and direction
- current speed and direction
- increase in power from level required to maintain same speed with no pressure

Pressure is primarily an issue of increased friction. In the Gulf of St. Lawrence and Baltic, the performance of the more powerful ships is degraded but the ships are rarely stopped. In Davis Strait, Baffin Bay and Lancaster Sound, the Arctic can be stopped but this occurs infrequently and then in late season voyages when the cold temperatures and snow create

high friction conditions. The most powerful ship, the Polar Star has been stopped in the Western Arctic. Other than increase power and change direction to head into the direction from which the pressure is coming, the master can do little until conditions improve and the ship can move again.

As pressure occurs in broken moving ice, many of the comments that apply there are applicable here. The comments in the following sub-sections are indications of how the design features influence the performance in pressured ice.

Bow Shape:

The high wedging or lateral forces at the shoulder of the Radisson are increased in pressure, increasing the resistance. This same tendency is shown on the Larsen by the severe degradation of the manoeuvring performance. Although no comments were made by the masters of the St. Laurent and MacDonald, similar angles in the shoulder regions would suggest similar phenomena. The masters of both the Oden and the Kontio comment favourably on the performance of the bows in pressure. These ships have relatively high flare angles. The track width of the Earl Grey is only as wide as the ship. This gives high frictional forces along the length of the parallel midbody and makes astern movement more difficult as the track closes that much sooner.

Bow Stopper:

In moderate pressure, the bow stopper of the Black contributes to the course control but the interaction with the ice hinders the manoeuvring.

Reamers:

The reamers of the Oden enhance the performance ahead by reducing the midbody friction, but degrade the performance astern as the ice closes in around them.

Length of Parallel/Shape Mid-Body:

The longer the length, the greater the friction, especially when travelling at right angles to the pressure direction. This is particularly true for the Arctic, Earl Grey and the 1100 class which also suffer severe degradation of manoeuvrability.

Sloped Midship Sides:

The only master to comment on the affect of the sloped midship sides was the MacDonald's. The slope on the MacDonald is 6 degrees. As the master of the Polar Star, which has a 12 degree slope, had no comment, the slope on the MacDonald is probably too small to have any noticeable effect. The master of the Larsen thought that the rounded shape of the MacDonald's

sides was better than the straight sides of his own ship.

Stern Shape and Propeller Arrangement:

The Earl Grey is even more difficult to back in pressure because the track closes, narrowing the track and increasing the ice concentration. The square stern is incapable of breaking the ice and pushing it aside.

Because of the reduced manoeuvrability in pressure, there is a greater tendency to use differential thrust to manoeuvre.

Because of an increased amount of propeller/ice interaction in pressure, the risk of damage to the propellers of the 1100 class is increased.

Bow Thruster:

Used on the Larsen to enhance manoeuvrability at low speed.

Friction Reduction Auxiliaries:

Used on the Larsen to reduce friction.

Heeling System:

The heeling system on the Radisson is used to free the ship if caught in pressure but is not used in the cycling mode.

Hull Coating:

As pressure is primarily an issue of increased friction, a good low friction coating or surface is essential for good performance.

3.2.7 Transit

Although transit was listed in the questionnaire as a performance category, it became obvious from the results of the questionnaire that it should be treated as a mission role. It was not obvious from the results how design features specifically related to transit performance. Transit is a mix of the other performance categories as follows:

- level ice
- ridges
- broken ice
- pressure
- manoeuvring
- propulsion
- open water

The percentage of each in transit will depend upon the

following factors:

- time of year
- weather
- route
- ice conditions

The role of the design features in transit must, therefore, be correlated with the weighting of each of the performance categories in the make-up of the intended transit.

3.2.8 Propulsion System

Although not strictly a performance category in the same sense as the different categories of ice and open water performance, the performance of the propulsion systems in ice may be affected by each of the design features of interest in the present study. It was, therefore, treated in the same manner. The major issue here is the effect of each of the features on the amount and type of propeller/ice interaction including blockage of the nozzle(s). This interaction is translated into loads on the propulsion system, the magnitude and frequency of which will determine the design and operating conditions of the propulsion system.

Bow Shape and Bow Stopper:

There is not a strong link between the performance of the propulsion system and the bow shape.

The lack of directional course control caused by the bow of the MacDonald increases the risk of damage to the wing propellers as the stern may swing into a floe. The bow of the Earl Grey seems to clear ice which prevents it getting into the screws. The bow of the Oden in conjunction with the bow wedge, midship shape and stern form minimize the amount of propeller/ice interaction.

The ice trapped by the bow stopper of the Martha Black is pushed along with the ship. When released, it tends to go straight into the propellers. In light ice conditions (3 to 4 tenths), ice will interact with the propellers of the Cornwallis when the vessel is proceeding at higher speeds.

Length of Parallel/Shape Mid-Body:

The Radisson lays down a large wake at high powers and higher speeds. Although this is effective in breaking ice, particularly when widening a channel for ice management duties, it becomes a problem in restricted waterways as it will damage shore facilities. The master must slow down in rivers and channels in open water. See comments above for Oden.

Stern Shape and Propeller Arrangement:

All the open propellers are susceptible to damage in heavy ice with multi-year ice present, and the operating procedures reflect this concern. This is particularly true on the Polar Star which does little manoeuvring astern and restricts the helm angle when turning ahead in heavy ice. Similarly the amount of astern manoeuvring in multi-year is restricted by the master of the St. Laurent and in first year ice by the master of the Cornwallis. The propellers of all the major icebreakers are well immersed and have adequate hull clearance for passage of most ice. When the ice becomes heavy, the hulls offer little protection to the ships with open propellers. The stern of the Oden is narrower than the midbody. This gives the ice broken at the bow, deflected by the wedge and midship shape and passing under the ship a location to exit clear of the propellers. On the MacDonald and the Arctic, the sterns have a tendency to tilt large floes which may interact with the propellers. The propellers of the Cornwallis are thought to be too close to the bottom, affecting the manoeuvrability in shallow water.

Propeller Type:

The propeller of the Martha Black is too weak for operations in the Western Arctic as evidenced by 5 breakages in two seasons despite care in operation. Although the Cornwallis operating in the Gulf of St. Lawrence has had limited exposure to old ice, she has damaged a blade when operating in old ice in the Strait of Belle Isle. The nozzled propeller of the Arctic is well protected from high loadings from operations in heavy ice and rarely has blockage. It must be borne in mind that she operates very conservatively astern due to the limitations of the steering system. The nozzles of the Oden protect the propellers in heavy ice but as she is operated aggressively in the Arctic blockage does occur. Blockage is very rare in Baltic operations, but in shallow water the suction from the propellers will pick up bottom debris and pass it through the nozzle. This has damaged blade edges. Despite the operating restrictions on the Polar Star, the centre propeller is switched over to the wing and the wings overhauled every two years. The upgrades to the propellers to remedy the original internal hub damage have improved the operating capabilities of the vessels, but have not allowed the ship to use her full capabilities.

Rudders:

The operation of the rudders is not linked to the propulsion system other than through the indirect link between restrictions on astern operations and risk of damage to the rudder/steering gear. On the Cornwallis the rudder top is not well protected by the stern.

Propulsion Control:

The major issues for the operators are machinery protection, response time, flexibility of propulsion plant usage and redundancy.

In all cases, the control system adequately protects the propulsion machinery from ice loads. On the Polar Star the increased amount of interaction on the outboard shaft in a turn can overload the shaft to the point that the control system will disconnect the shaft. In the gas turbine mode, it will take 10 to 15 minutes to get the shaft back on line. To avoid this the operator will reduce the propeller pitch on the affected shaft when he detects the onset of the overload condition. Although avoiding the downtime if the shaft were to go off line, the ship suffers a decrease in performance. If full power is not required on all shafts, the centre propeller will be given a larger percentage of the total power to avoid overloading the wings. When the system on the Larsen trips on overload it can take 20 minutes to get the system back on line.

The system response times (full ahead/full astern) on the vessels are:

Ship	Time - Seconds
Polar Star	40
Louis S. St. Laurent	6
John A. MacDonald	15
Pierre Radisson	10 to 12
Henry Larsen	10
Martha Black	14 to 20
Edward Cornwallis	11
Earl Grey	12
Arctic	40
Oden	6
Kontio	20

The times are judged to be good on the St. Laurent, MacDonald, Larsen, Cornwallis, Oden and Kontio, adequate on the Star, Radisson, Black and Grey and deficient on the Arctic. The masters of the Black and the Grey think that a time of 8 to 10 seconds would be ideal. Although the master of the Radisson thinks the time is fast enough, the requirement to pause through the 0 thrust position is an operational annoyance. As an overall ranking the master of the Kontio rates the time as good. However, for operations involving frequent thrust reversals (ridge ramming and star manoeuvres), the time is too slow and affects the speed of the operation. As seen in the table, the response times of the Polar Star and the Arctic are similar, although the rankings of these times are quite different. As the power to displacement ratios (kW/tonne) of the two vessels differ by a factor of more than 10 (3.4 for the Star versus 0.3 for the Arctic), this factor clearly plays a role in the selection of the time.

The master of the Polar Star thinks the control system allows the propulsion system to be used flexibly and offers good redundancy as he has the choice of three shafts and diesel electric and gas turbine modes on each shaft. This is gained at the expense of high manning and maintenance. The system on the Radisson (twin screw, diesel electric AC/DC with 8 diesel engines) offers an infinite variety of revolutions (down to 5 rpm) with no creep and the ability to switch two of the diesels from port to starboard shafts or vice versa. The large number of diesels with limited capability to share power between the shafts creates a system with limited flexibility. The master would much prefer a central power plant concept where the power would be used as required. The AC/AC system on the Larsen is designed as a central power plant concept (as are the systems on the 1100 class). It allows efficient utilization of the engines at varying speeds while offering equal power to each shaft. The control systems on the Larsen and 1100 class Martha Black suffered reliability problems when they first went into service and the inability to maintain the systems by onboard personnel is an ongoing concern. The master of the Cornwallis thinks that the propulsion system is unnecessarily complex for the vessels missions.

3.2.9 Open Water

The ships in the present study operate in a wide variety of open water conditions. The Arctic spends as much as 65% of her operational time in open water voyages, primarily in the North Atlantic. The four large CCG icebreakers (St. Laurent, MacDonald, Radisson and Larsen) make yearly voyages to the Arctic from their eastern Canadian bases to escort ships for the summer resupply. The Black has made two voyages to the western Arctic from her west coast Canadian base for the summer resupply and spends the rest of the year buoy handling on the west coast. This involves about 75 to 80 % open water operation. The Cornwallis operates in the Gulf and eastern Canadian waters in the summer spending about 60% of her operational time in open water. The Grey handles buoys in the Gulf of St. Lawrence when not icebreaking in the winter months. The Polar Star operates out of Seattle, Washington and performs the breakout of McMurdo Sound in the Antarctic and escorts ships to Thule in Greenland. The Oden spends about 10% of her Baltic operational time and about 20% of her Arctic operational time in open water. The Arctic time would involve exposure to North Atlantic conditions. The Kontio only operates in the Baltic and has little exposure to open water operations (about 8%).

Bow Shapes:

Without good full scale speed and powering information and a base ship standard, the role of the bow shape in open water resistance is not readily quantifiable from observation alone. The hull form of the Oden is optimized for ice operations and

she clearly pays a penalty in calm open water resistance.

As described in the introduction, many of these ships spend considerable operational time in open water. The voyages or operating areas are in locations that can develop severe wave conditions coupled with high winds. The universal concern is therefore seakeeping. For the bow this involves slamming or pounding and wetness.

With the exception of the Arctic, the MacDonald and the Oden slamming/pounding is not a problem. On the Arctic, the high flare angles cause pounding which translates into high global bending loads. To avoid this the master reduces speed in ahead seas in excess of sea state four. In sea state six, the power is reduced to the point where the ship makes about 6 knots against the waves. The bow of the MacDonald slams in severe sea states. Although the bows of the MacDonald and the St. Laurent are similar at the operating waterlines, the lack of a forefoot stopper on the MacDonald creates much flatter bilge sections than on the St. Laurent. The very flat sections of the Oden's bow pound. Based on the comments of the masters, it would appear that those ships with average bow flare angles (see table 2.3) of over approximately 45 degrees suffer from pounding. Ships such as the Kontio (42.8 degrees) and Polar Star (45.2 degrees) consider pounding/slamming to be satisfactory.

In severe conditions the bows of the Polar Star, St. Laurent, MacDonald, Radisson, Larsen, Oden and Kontio are wet. Wetness coupled with ship motions (rolling and pitching) are the reasons for voluntary speed reductions by the masters of these vessels. The low freeboards on the MacDonald and the Radisson contribute to the wetness. The addition of the forecastle on the Larsen may have improved the wetness right forward but the ship is very wet aft. Even in relatively calm conditions spray keeps the decks wet. This is thought to be due to the large bow wave when the ship is driven at high powers. On the Arctic, wetness is not a concern as the ship has a high freeboard forward, and an aft wheelhouse location. In addition, this ship slows down because of pounding before wetness becomes an issue. The bow designs of the 1100 class Black and the Grey were optimized in favour of open water operation and this is reflected in the operators' positive comments about seakeeping. In general those ships with the finer bows (Kontio, Polar Star, Radisson) and wall sided (MacDonald) rated pitching behaviour as deficient or unsatisfactory. The Oden with a short bow is rated good for pitch.

The size of the wake generated on the MacDonald, 'R' class, 1100 class, Oden and Kontio is a concern for operation in restricted waterways because of the risk of damage to shore facilities. Speed reductions are therefore required. The bow shape of the Black (including the bow stopper) is thought to contribute to the high power requirements above 12.5 knots.

Shape of Midbody:

The large radius bilges, particularly on the St. Laurent and the MacDonald, combined with the lack of bilge keels and the high GM's are the cause of the large amplitude and fast rolling of the major icebreakers. The Oden is given a good rating for rolling due largely to the damping characteristics of the midbody shape. In general, crew comfort when rolling is a major operational concern.

Stern Shape and Propeller Arrangement:

The fine stern of the Polar Star is wet in severe conditions as it lacks buoyancy and has a low freeboard in comparison to the bow.

The manoeuvrability of the multiple screw ships in open water is enhanced by the use of differential thrust on the propellers. This effect can be reduced if the propellers are close to the centreline as on the twin screw Martha Black and Oden. Conversely if the ship is required to operate on one screw, having the propeller close to centreline makes course keeping easier. The lack of differential thrust on the single screw Arctic is an operational disadvantage especially with a bow thruster that is not powerful enough to manoeuvre the ship efficiently,particularly with any beam wind present. The manoeuvrability astern of both the Oden and the Kontio is poor. The propellers of the Cornwallis are thought to be too close to the bottom and the manoeuvrability is degraded in shallow water. The redundancy of multiple screws is considered an advantage by the masters of the Polar Star and the Radisson.

The Larsen suffers from pronounced vibration at high powers.

Propeller Type:

The propellers on the Polar Star have been optimized for low speed operation in ice to obtain thrust and hence are less suitable for higher speeds in open water. At slow speeds with 0 pitch, the nozzled controllable pitch propellers of the Arctic and the Earl Grey mask the flow to the rudders. This causes lack of manoeuvrability and poor course keeping. Thus coasting up to a pier or buoy with the vessel under control is not possible. As high fuel consumption is a major concern on the St. Laurent, the master would like to be able to operate the ship on the centreline shaft in open water. The wing propellers on the St. Laurent can not be trailed, requiring all the propellers to be powered. This adds to the high fuel consumption of this vessel.

Rudders:

The blanking of the rudders by the nozzled propellers of

the Arctic and the Grey has been discussed above. The rudders are in the wake of the centreline propellers on the triple screw icebreakers Polar Star, St. Laurent and MacDonald and on the twin screw, twin rudder ships (Grey, Oden and Kontio) and provide good manoeuvrability with no helm response delay. Conversely the single rudder twin screw ships, Radisson, Larsen, Cornwallis and Black are slow to respond to a helm order (15, 8, 6 and 6 seconds respectively) as the rudder does not operate in the slipstream of the propellers until large rudder angles are achieved. The propellers of the Black are closer to the centreline than on the Radisson and hence the rudder operates in the wake of the propellers at lower angles, increasing its effectiveness. The astern manoeuvrability of the Cornwallis (without the use of the bow thruster), Oden and Kontio are poor. This is thought to be due to the closeness of the propellers to the centreline on the three ships and to the minimum amount of deadwood on the Kontio.

Propulsion Control:

The key issues are flexibility and complexity of propulsion plant operation and ahead/astern response time.

For the Polar Star and the MacDonald flexibility is the ability to operate economically at different speeds by being able to choose the right combination of engines operating at efficient power levels to achieve a given speed. The system on the St. Laurent (before refit) was inflexible. All the shafts must be powered. At an economical speed of 10 to 11 knots, the ship can be operated on 2 boilers and 3 generators and burns about 65 to 70 tonnes per day. However the ship is sluggish to operate and to have a reserve of power 3 boilers are used to leave harbour. At maximum power in ice the ship uses up to 210 tonnes of fuel per day with 3 boilers (1 standby) and 9 generators. On the Radisson, the system is considered flexible as it is possible to control the rpm to fine limits. On the Martha Black, the ship is overpowered for open water service as it is uneconomical to operate in excess of 12.5 knots as the speed/power curve becomes very steep beyond this speed. The AC/AC system on the Cornwallis which offers infinite variation of the RPM, is thought to be far too complex for the type of operations undertaken by the ship.

The ahead/astern time of the Arctic is too slow (40 seconds) for efficient low speed manoeuvring.

Thrusters:

The bow thrusters on the Radisson, 1100 class and the Grey are powerful enough and are used in open water to assist low speed manoeuvring. The thrusters on the Arctic and the St. Laurent are not reliable and are seldom used. The bubblers on the Arctic and Kontio when used in the thruster mode are not as effective as a conventional thruster for the amount of power used. The thruster (bubbler) on the Larsen is effective and

acts as a cushion between the ship and the pier. The stern thruster on the Grey is powerful enough.

Heeling and Flume Systems:

The flume systems on the MacDonald and the St. Laurent reduce the roll amplitude by more than 50 % and on the Radisson by about 30%. In severe seas this is still unacceptable as the amplitude is still significant and the roll period is very fast producing high accelerations. The flume system on the 1100 class is effective in reducing both the amplitude and the roll frequency. The flume system on the Black can not be frozen quickly when recovering buoys and is not used as it causes additional heel angle. This does not appear to be a problem for the operations of the Cornwallis in east coast operations. As the master of the Larsen rates his ship good in rolling, the intering system appears to effective. The free surface of the heeling system on the Oden reduces the GM sufficiently that the severity of rolling is reduced.

3.3.10 Overview of Performance Categories:

At the end of the questions for each performance category, the masters were asked to give the ranking of the vessel's overall performance in the performance category. The rankings on a scale of 1+ (excellent) to -1 (unacceptable) are given in table 3.4.

The rankings represent the ability to perform in each performance category in all conditions encountered, not just the most severe. As a result, some of the design deficiencies discussed in the previous sections are masked by the infrequent occurrence of the limiting conditions in which these deficiencies occur. In addition, it must be borne in mind that the masters are basing their rankings on experience with other icebreakers with which they are familiar.

The master of the Polar Star is compering the performance of his ship with that of the Glacier. The Glacier has about one third the power of the Polar Star and has an old design 30 degree bow. In most performance categories, the Polar Star has vastly superior performance, hence the excellent rankings. In ridges the tendency to stick at the shoulders, down grades the performance to good. The vulnerability of the wing screws to propeller/ice interaction, causing the restrictions on turning performance and backing, down-grades the ranking of the propulsion system. As with most heavy icebreakers, the performance in rough open water is poor due to the extreme motions.

The masters of the St. Laurent and the MacDonald are using each others ships as the main reference for rankings. As the performance of these ships is similar, the rankings tend to be the same. These ships do little heavy icebreaking in the Arctic and hence the deficiencies discussed in the previous sections have little weight in the overall ranking. The masters are

aware that the performance of these ships is not as good as the newer ships, but as they are able to accomplish their missions with little difficulty, hence the good ranking for most of the categories.

The master of the Radisson is comparing the performance of his ship to the Mudyug and the Kalvik. In most categories the performance of these ships is superior, yet the Radisson is able to perform her assigned missions. Rankings are therefore good or adequate. For ridge performance, the ship tends to stick at the shoulders and does not penetrate ridges effectively. In manoeuvring the difficulty in breaking out of a channel and the lag in helm response degrade the ranking. The propulsion system is superior to either of the comparison ships because of faster response time and better protection.

The master of the Henry Larsen has had limited Arctic operation with his ship and therefore the rankings are primarily for Gulf of St. Lawrence operations. The comparison ship is the John A. MacDonald. Both ships are primarily involved in escort and have approximately the same power, but the Larsen has a bubbler and less beam (19.5 m versus 21.3 m). The bubbler has reduced the tendency to stick in high friction conditions and the newer hull form gives the Larsen greater icebreaking capabilities. Hence the 1+ rating for level ice performance. In pressure the ship is an improvement over the MacDonald (the ship has not been stopped in Gulf conditions), which would explain the 1+ rating for pressure. In Gulf operations the ship performs well in all categories with no major vices to impede execution of her missions.

The Martha black is not suitable for operation in the heavy ice of the Western Arctic. The propellers are too weak, and are not well protected by the hull. In addition the hull has insufficient strength for aggressive icebreaking which may be required to assist escorted ships. The lack of manoeuvrability, primarily due to the length of parallel midbody, makes it difficult to perform the missions.

The Cornwallis has only operated in first year ice in the Gulf of St. Lawrence. She is able to perform her missions in all the ice and open water conditions encountered. Comparisons are made with other vessels which the master has commanded while performing similar missions. The master has commanded the MacDonald and hence is familiar with more powerful ships. In the ice thicknesses encountered the ship is able to perform the majority of level icebreaking ahead. The newer hull form of the ship and higher power gives her much better level ice performance than the ships which she replaces. Hence the 1+ rating for level ice. In ridges and broken ice the stopper degrades the performance. In pressure the length of parallel midbody can severely degrade the performance. The propulsion has been unreliable and is too complex, hence only a satisfactory rating. In open water the ship is manoeuvrable and receives a good rating for seakeeping. In comparison to pure icebreakers such as the

MacDonald she is excellent.

The Earl Grey has a much higher power to displacement ratio than the comparison ships and is able to perform in most conditions in the Gulf of St. Lawrence with ease. The long parallel midbody length makes manoeuvring difficult in high ice concentrations and degrades the ranking. In pressure, the narrow track closes in immediately behind the ship, making it difficult for an escorted ship to follow. Yet when operating alone in pressure the ship has sufficient power to perform well.

The master of the Arctic is comparing the performance of his ship to the Arctic with the old bow. The 50% improvement in level icebreaking performance enables the Arctic to perform much better in the thick ice in the first run into Admiralty Inlet each season. Although she is able to manoeuvre in conditions in which the old ship could only ram in a straight line, the slow rate of manoeuvring due to the very long midbody length gives an only acceptable ranking for manoeuvrability. In heavy ice conditions, the ship has no reserve power and stops with very little pressure due to the increased friction on the long parallel midbody.

The Oden is compared to the older generation Baltic icebreakers. With increased power and displacement and the thrust augment from the nozzles coupled with the more efficient hull form (in ice), the ship is a big improvement over the earlier ships in ice. The poor astern capability is not an operational problem as the ship turns so well ahead that she uses this capability to overcome the astern deficiencies. In open water, the ship is rated higher in most aspects of seakeeping and the higher resistance in calm water is not a major concern for the practical operating speeds.

The Kontio is compared to the same ships as the Oden. In most categories she is rated as good. In level ice, although she has reduced resistance, she is downgraded because of the poor astern control and manoeuvrability. In most aspects of open water performance she is worse than the older generation of ships (particularly in seakeeping) and hence is given a deficient rating.

3.3 Mission Roles

3.3.1 Introduction

Table 3.5 summarizes the ability of each of the ships in the study to perform their mission role. All of the ships are able to perform their mission roles with varying degrees of success. A discussion of the requirements of the mission and the ranking in the table is given in the following sections. It should be borne in mind that the rankings given by the masters are based on their own operating experience and in particular on comparisons with the ships which they have commanded pre-

viously. Thus the rankings should not be used to compare the performance between ships, especially as the ships have different ice management duties and operate in different ice conditions.

3.3.2 Ice Management

Ice management involves two different operations; channel maintenance and harbour breakout. The six east coast CCG ships, St. Laurent, MacDonald, Radisson, Larsen, Cornwallis and Grey open and maintain channels and breakout harbours primarily in the spring. The Radisson's channel operations in the St. Lawrence River involve somewhat different factors as the flow of the river in the narrower sections can build up ice jams of deep brash and deep frazil ice can be encountered. These factors are not seen in the Gulf of St. Lawrence operations. The Polar Star opens up a channel into McMurdo Sound to permit resupply in the Antarctic spring. This involve cutting a large wedge shape in the ice field with the purpose of having the wind remove the whole wedge or if the prevailing winds are across the channel to blow the wedge against the secondary channel, leaving the primary channel clear. To accomplish the latter objective the secondary channel is made about 150 m wide and broken into small pieces by making 6 or 7 passes through it. In addition Antarctic operations may involve channel widening in thick ice, where an 8 to 10 m slice is scarphed off the channel edge. The Oden and Kontio perform ice management missions in the Baltic. The Oden performs both channel and harbour operations, but only about 5% of her operational time. The Kontio performs channel operations about 20% of the time but these are considered part of ice escort. The Arctic's ice management duties involve clearing the dock face of ice at locations such as Nanisivik to permit the ship to load cargo.

The primary factors in making a channel are the abilities to make as wide a channel as possible in a single pass and to have that channel as clear as possible of ice.

For channel maintenance, the factors are the ability to maintain speed in the channel, manoeuvrability and the ability to operate in deep brash and high friction conditions.

For harbour breakout the factors are the size of the ice pieces broken in a single pass, manoeuvrability (particularly the ability to work closely to shore facilities), shallow water operation and the ability to break through deep ridges or rubble fields at the entrances to harbours.

The Arctic's operation involves making a single pass as close to the dock as possible and then using the propeller to flush the ice away from the dock.

The ranking of the Polar Star is based its superior ice-breaking capability when compared to the Glacier. The Star is able to maintain continuous progress in the 1.8 to 2.0 m summer

ice in McMurdo Sound, whereas the Glacier would be ramming. The reduction in the time to break into the base is dramatic. In addition the continuous progress helps to maintain a straight edge to the channel which is beneficial for the inbound cargo ships. A lot of ice goes through the propellers of the Star which ensures the ice is broken into small pieces in the secondary channel described above. The Star is able to widen a channel by scarphing off about 8 to 10 m of the edge in a single pass. The Glacier would have a lot of difficulty in performing this task.

The masters of the St. Laurent and the MacDonald compare the performances of their own ship with that of the other. As the performances of the ships are similar, the rankings are similar. In channel operation both ships are able to maintain good speed in a broken channel and are manoeuvrable. They have enough power to operate in deep brash, but a bubbler or other effective friction reduction auxiliary would be of benefit in high friction conditions. Both have deep drafts which limits shallow water operation. In harbour breakout both ships are very manoeuvrable with differential thrust used to manoeuvre in tight quarters. Both ships tend to stick in the thick ridges at harbour entrances, but the St. Laurent has the performance edge due to the greater displacement and power. Both masters would like the ships to break the ice into small pieces to minimize the number of passes required in the harbour. Both masters are careful around shore facilities to avoid damaging them as the low flare bows push ice laterally.

In making a channel the master of the Radisson compares the performance of his ship with that of the Mudyug. The Mudyug has a Waas bow which leaves a relatively clear channel with straight edges, whereas the Radisson leaves a lot of ice in the channel. The large wake is useful in channel widening as it breaks the ice either side when a high speed pass is made down the channel. In channel maintenance, the Radisson is able to maintain good speed (about 11 knots) and is manoeuvrable. Manoeuvring tends to be with differential thrust on the two propellers due to the lag in response to a helm order. In deep brash, a bubbler or other friction reduction auxiliary would assist operations. In addition, sea suction has been a problem in deep brash.

The performance of the Larsen is compared with the MacDonald. In channel operations the better manoeuvrability of the MacDonald gives her an advantage but in high friction conditions the bubbler of the Larsen is advantageous. In harbour operations the greater displacement of the MacDonald gives her an advantage in breaking through thick old ridged ice but the bubbler of the Larsen is better in high friction conditions and acts as a fender to keep the ship away from piers.

In channel operations the Cornwallis is hard to manoeuvre at low speed and is difficult to keep in the channel. In shallow water, the ship is difficult to manoeuvre due to bottom

effects. She will widen a channel by 3 to 6 m by crabbing down the channel although she is difficult to keep on the ice edge. In harbour operations, the master tries to take advantage of the large wake by operating at high speed to break a path wider than the ship. The shallow water manoeuvrability degradation is encountered more often in this operation. In comparison to the MacDonald, the smaller size is much handier for most operations but for operation in thick ridged ice the power and displacement of the MacDonald are advantageous.

The master of the Earl Grey is comparing the performance of his ship with the earlier generation of light icebreaker/buoy handling vessels. The Grey is far more powerful, but because of the length of the parallel midbody does not manoeuvre as well. The size of the wake on the Grey is small meaning that for harbour breakout every piece must be broken, rather than having the wake break up a wider track as the vessel passes through the harbour at high speed. The track width when cutting a first channel in ice is only as wide as the ship. In shallow water operation the vessel squats more than the earlier vessels. Despite these shortcomings, the power of the vessel is more than adequate for the ice conditions in which she operates and the operator gives the vessel a good ranking.

The power and manoeuvrability of the Oden give her good capabilities in both channel and harbour operations. She does a better job than the older generation icebreakers in breaking up the ice and clearing it, but the bottom suction and resulting squat are a problem in shallow water operation. Astern operations are worse than the older generation ships as she accumulates ice astern slowing progress and the manoeuvrablity astern is poor.

The Kontio has an equal rank to the older generation icebreakers. She is generally better in ahead operations because of the hull form and power. Astern, the lack of control and manoeuvrability downgrade the performance in comparison to the older ships. The bow propellers on the older ships give more precise control both ahead and astern.

The increased icebreaking capabilities of the new bow of the Arctic permit her to perform the manoeuvre described above, whereas the old ship was not able to operate in the 1.5 m ice thickness without resorting to ramming.

3.3.3 Towing

Successful towing is dependent upon towing equipment and power.

Five of the masters have used their ships to tow in ice. The ships are Polar Star, John A. MacDonald, Martha Black, Oden and Kontio. The Oden and Kontio are properly equipped with winches and towing notches and towing is part of the ice escort

role. The other three ships are not well equipped and towing is carried out on a limited basis.

The three ships which perform limited towing are not equipped with stern notches or stern fendering arrangements. The tows on the ships are from bollards, towing bitts or mooring capstans. The MacDonald tows small fishing vessels in broken ice as part of SAR. The Star has assisted a 30,000 tonne ice strengthened tanker away form an ice pier in the Antarctic. This involved towing the tanker stern first from the Star's bow into a turning area and then bow first to assist in turning. The Black tows tugs and barges when it is not possible to escort the ships in pressure or heavy ice in any other manner. In open pack this would be on a 45 to 60 m line, whereas in heavy conditions the tow would only be about 8 m. The lack of any stern fendering for the close tow gives a high risk of damage to the Black's transom if overrun by the towed vessel.

In the Baltic both the Oden and Kontio tow ships in ice when the escorted ships are no longer capable of following in the track. This would occur in pressure or in thick ice. The ships have displacements up to about the displacement of the icebreaker. The equipment and location of equipment on the Oden are good enabling the ship to tow under good control. The size of the rudders and their location in the wake gives fast and powerful response. The master would like to have increased thickness of rubber in the towing notch to more securely locate the towed ship. On the Kontio the ship has adequate power and rarely needs to use full power when towing. Again the need for good control was mentioned as a prime requirement. The winch on the ship is too far aft and too low making the tow harder to control.

Although he does not tow, in ice the master of the Radisson commented that his operating efficiency would be increased significantly if he had the capability to tow underpowered vessels heavy ice conditions.

The master of the Cornwallis does not tow in ice but in open water tows the visibility aft from the wheelhouse is poor.

3.3.4 Buoy Handling

Only three of the ships handle buoys as a prime mission; the Martha Black, the Edward Cornwallis and the Earl Grey. A negligible amount of this is in ice. The masters rank their ships as good or excellent when comparing the performance with their former commands. The vessels have better equipment and manoeuvrability.

The flare of the bow on the Black makes a bow on approach to the buoy impossible, but this does not affect the operation significantly. The flume tank, at operating level, causes additional heel when recovering buoys and is not filled when performing this mission. With the boom rigged forward on the Cornwallis, buoy recovery can be difficult when backing away in

wind or current. The forward deck is too small as it will only handle one days work. As discussed in previous sections the manoeuvrability is degraded in shallow water. The visibility from the wheelhouse is poor as it is impossible to look down at the vessel's sides. The low stern on the Grey limits the wave height in which buoys can be recovered to about 1.2 to about 2.5 m. The stern recovery area on the Grey means that the whole ship must be brought in closer to the buoy and hence the shallower water. As the CPP does not stop turning when in neutral it has a greater tendency to pick up gear. In addition, the CPP nozzle combination gives a loss of steerage when coasting up to a buoy.

3.3.5 Ice Escort

The vessels being escorted are generally of a much lower ice class and, hence, benefit from a wide clear track. In severe ice conditions, the escorted vessel may become stuck and require assistance from the icebreaker. Manoeuvrability, especially the ability to back down on the escorted ship, then becomes important. The ability to widen an existing channel is important for escorting a ship wider than the icebreaker.

The Polar Star escorts larger ships (up to 180 m length by 30 m beam 30,000 tonne dwt tanker) into Thule Greenland in July. If the vessel becomes stuck the Star turns around to assist as backing up and around the vessel is not done due the high risk of propeller damage. Channel widening is not required. The large power gives the Star considerable advantages over the comperison ship, the Glacier.

The Louis S. St. Laurent and the John A. MacDonald have comparable performance. Because of the triple screws, both ships have excellent manoeuvrability especially astern when the ships back down to assist a beset vessel and when operating close to another vessel. When assisting another vessel, both masters will choose the most time effective manoeuvre, which will depend upon the environmental conditions. The manoeuvre of choice is to back up and operate around the beset vessel. The masters of both vessels rank the amount of ice in the track as only acceptable. Both vessels are able to widen an existing track up to about 50% of the beam by crabbing the vessel along the track using the rudder. The wider beam of the St. Laurent gives her an advantage when escorting wider ships. On the MacDonald, the tendency of the bow to be deflected off stronger ice can give difficulty when operating close to another vessel. Both masters complain of poor visibility aft for monitoring the escorted vessel(s).

The Radisson performs well in breaking the track ahead and when assisting a beset vessel by backing, turning and breaking parallel to the vessel and when operating close to the vessel. The freshly broken track has a lot of rubble, but the piece size is decreased at higher speeds. The ship widens a channel in thinner ice effectively with her large wake, but in thicker

ice, she tends to fall back into the old channel because of the bow shape and the partially effective rudder. Backing up and around the beset vessel is the manoeuvre of choice. As for the previous two ships visibility aft is poor. The comparison ship, the Mudyug makes a clear channel and can widen a track with ease. In addition, the runners of the Mudyug give good manoeuvrability, and control when operating close to another vessel. The Mudyug has poor backing capabilities. The ability of the Mudyug to tow also gives her an advantage over the Radisson.

The Larsen escorts ships in the Gulf of St. Lawrence, most of which are wider than the Larsen. They range in size from 1500 to 50,000 GRT. The vessel is rated as good for all aspects of escort performance. She performs the same as the MacDonald in all performance components of escort except backing up and around the vessel where the triple screws of the MacDonald give her better astern manoeuvrability. The bubbler aids the escorted ship by widening the track in lighter ice conditions and by wetting the ice between the icebreaker and the escorted ship when beset.

The Martha Black has enough power to do a good job of breaking the track ahead and she makes a good track for following vessels which are not as wide. Because of the difficulty in manoeuvring, she has difficulty in turning around to widen the track. Widening the track consists of making a second pass about 10 m to one side of the existing track as she tends to fall back into the existing track if the distance is any smaller. The manoeuvre of choice is to turn around and break parallel to the beset vessel. This is difficult because of the poor manoeuvrability. Backing up is not a choice because of the risk of damage to the propellers and the poor astern performance. When working close to the beset vessel, care must be taken as the vessel has a tendency to follow the path of least resistance.

The Cornwallis escorts ships in the Gulf of St. Lawrence, 90% of which are wider than the Cornwallis. Escort comprises about 80 to 85% of total operational time in ice. The ship does a good job of the escort component of the mission (i.e. breaking the track ahead, maintaining a clear and widening an existing channel) but only a satisfactory job of freeing a beset vessel. The escort component involves ahead motion which the vessel does well especially at higher speeds when the large wake breaks a track wider than the ship. When freeing the beset vessel backing up and around the escorted vessel is the manoeuvre of choice 95% of the time. In thicker ice conditions, the ship is not manoeuvrable astern as most of the power must be used to maintain astern way. In addition the length of parallel midbody gives the ship a large turning diameter which makes assisting the beset vessel by turning and breaking parallel difficult in thick ice. In comparing the Cornwallis to the MacDonald, the Cornwallis has equivalent performance in maintaining a clear track, widening the channel and working very closely to the beset vessel. The greater power and better

manoeuvrability of the MacDonald give her the advantage in breaking the track ahead and freeing the beset vessel by either backing or turning. The visibility from the wheelhouse of the Cornwallis is poor for escort operations.

The Earl Grey has more than enough power to escort well ahead. The majority of the ships which she escorts have wider beams. In high concentrations, the ship only makes a track as wide as the beam, which gives wider ships difficulty in following. In addition the track has a lot of ice in it. She can widen an existing track by crabbing. As the ship has no astern capability in any significant ice thickness, she can only assist a beset vessel by turning around. This manoeuvre is time consuming because of the poor ahead turning due to the length of the parallel midbody.

The Kontio spends about 70 percent of her operational time in ice actually escorting ships. The ships range in size from 1,300 to 50,000 tonnes deadweight, but the common range is 2,000 to 20,000 tonnes. The power of the escorted ranges from 2,000 to 12,000 horsepower with the occasional ship having 15,000 horsepower. The ship does a good to excellent job of the escort component of the mission (breaking ahead, clear track and channel widening) but has mixed results when freeing a beset vessel. She does a good job of turning and breaking parallel to the beset vessel and a satisfactory job of working closely to the vessel. Backing up and around the vessel is rated as deficient. This is particularly critical as backing is the manoeuvre of choice for assisting the beset vessel. The reasons for this are clear form a comparison with the earlier generation of ships with bow and stern propellers. The quadruple screw ships have much better control and manoeuvrability astern and much better control when manoeuvring close to another vessel. When escorting, the bubbler of the Kontio is used to clear the track and the rudders are toed out to accomplish the same thing. The escorted ship is kept close to the icebreaker to utilize the clear track immediately aft of the icebreaker. As towing is an essential element of Baltic ice escort, the description of the Kontio's towing performance in section 3.3.3 should be considered in the overall evaluation of escort performance.

The Oden spends about 50% of her operational time in ice escort while operating in the Baltic. She is rated as excellent for all aspects of escort and freeing the beset vessel except freeing the beset vessel by backing up, where she is rated as deficient. Because of the ice accumulation at the stern and the reamers, the ship has poor astern performance. In the escort mission this deficiency is not of major concern as the ship is able to turn very well ahead in all ice thicknesses. Thus the manoeuvre of choice for freeing the beset vessel is to turn around and run parallel to the escorted vessel. In the overall ranking of the escort performance components backing is last. When compared with the older generation of quadruple screw ships, the Oden is better in breaking ahead and maintaining a

clear track and much better in widening an existing channel and turning and breaking parallel and working closely to a beset vessel. The Oden is worse in manoeuvres requiring astern operation.

3.3.6 Supply

With the exception of the 1100 class, supply is a minor role for the ships in this study. The Arctic is a cargo ship with commercial delivery of bulk and oil cargoes her prime mission.

The large icebreakers, Polar Star, St. Laurent, MacDonald and Radisson only delivery small amounts of cargo to destinations that are inaccessible to commercial ships. The prime considerations are cargo capacity and deck layout, as well as the cargo handling gear. Anchoring at the destination is also important. The R class tends to shver in high winds which may cause them to drag their anchors.

The Martha Black delivers supplies to navigational aids stations along the B. C. coast and one off types of cargo to the Arctic. She has good cargo space and handling equipment and a variety of boats to land cargo. She handles well and hence docking is easy. Although she remains at anchor in high winds, the anchor arrangement is not satisfactory.

The Cornwallis does all of her supply duties in open water, spending about 5% of her operational time in this mission. She is on government operations carrying construction materials to locations such as Cape Breton and Sable Island. She is good in docking and anchoring and satisfactory in deck capacity and layout, cargo hold capacity and cargo handling gear. For the missions undertaken, the master would like to have more room aft as the flight deck is small.

The Arctic has a good hold arrangement for bulk cargoes, but only an acceptable tank arrangement for oil cargoes. The handling gear is good and she has no anchoring problems. The single screw and ineffective bow thruster make going alongside difficult.

3.3.7 Search and Rescue

This is not a major role for the ships in this study. The process involves the following steps:

- getting to the location
- remaining alongside the vessel or person to be recovered
- recovery
- towing

Getting to the location involves open water speed and seakeeping. Remaining alongside involves low speed manoeuvring and station keeping. Recovery either means over the side

recovery from the vessel or putting auxiliary vessels into the water to recover people. Vessels requiring assistance are towed out of danger or to port.

All the large vessels including the 1100 class have difficulty in over the side recovery because of the large freeboards. In addition the rolling of all of these vessels in any significant seaway (with the exception of the 1100 class and Larsen which have effective anti-rolling tanks and the Oden where rolling is damped by the hull form) makes over the side recovery or boat launching hazardous. Recovery tends to be with the auxiliary boats or with a crane and personnel ring if fitted. Lack of equipment on some of the vessel is a deterrent for efficient SAR work. The wake size of the Black is too large. These vessels are in general too large for towing the smaller vessels which they may need to rescue on an opportunity basis. The draft on the Kontio is too large for inshore work. Seakeeping abilities of these vessels have been discussed in an earlier section.

In general these vessels are too large and uneconomical for SAR to be a primary role without compromising other missions. They are therefore used only if nothing else is available. As suggested by the master of the Radisson, the best role for the larger vessels in a SAR mission is to act as the command and control centre coordinating the activities of other vessels. Their ability to get to the scene and remain on station are the main factors for this role.

3.3.8 Transit

As discussed in section 3.2.7, transit is a mix of the performance categories the weighting of which depends upon the environmental conditions.

The reference transit for the Polar Star was in Baffin Bay in July in 8 to 10 tenths cover about 1 m thick with ridging 3 to 4 m high. In these conditions, propeller/ice interaction is the major concern as it restricts the ability to use the full power of 44.7 MW.

Transits for the St. Laurent and the MacDonald are either in the Gulf of St. Lawrence in the winter or to the Arctic in the summer. The summer transits are dominated by open water consideration, particularly seakeeping and for the St. Laurent fuel consumption. In the Arctic the ships avoid heavy ice features because of the danger of damage from multi-year ice. In the Gulf, both masters try to avoid ridges because of the tendency to get stuck. Manoeuvring is therefore important to avoid ridges. Pressured ice can slow progress and neither ship has a large reserve of power in thick ice to overcome the additional resistance. The difference in the rankings is due to the larger emphasis placed on open water performance by the master of the MacDonald.

The Radisson operates in the Gulf and River St. Lawrence and on voyages to the Arctic. The master therefore has similar concerns to those of the masters of the St. Laurent and the MacDonald. In open water, it is not possible to use less than 4 generators which limits the flexibility of the propulsion system.

The reference transit for the Larsen is in the Gulf of St. Lawrence as the ship has had limited experience in the Arctic. Concerns are generally similar to those for the other major Canadian IceBreakers. In Gulf operations agglomerated brash and pressure are the major impediments to fast transits. The propulsion system is more flexible than the Radisson's, but this has been gained at the expense of considerable reliability problems at the start of operations and on the ongoing concern about maintenance of a complex system.

The reference transit of the Martha Black is in the western Arctic from Herschel Island to Barrow in October with 4 tenths multi-year ice and 5 tenths plus of first year ice. In these conditions the ship has enough power that the forward mode tends to dominate and the poor astern performance and the risk of propeller damage are not dominant considerations. The strength of the ship limits the speed in multi-year ice to 1 to 2 knots or about 8 knots in thick first year ice. An operational problem is the inability to ballast the ship to compensate for fuel usage. As the fuel is used the draft decreases, increasing the risk of propeller damage. The master takes on fuel in Tuktoyuktuk to get through the ice on the homeward trip with a deep draft, although the remaining fuel would give the ship sufficient range for the voyage.

The reference transit for the Cornwallis is in the Gulf of St. Lawrence. This transit has been carried out at 8 to 10 knots average speed. She performs well in all aspects of transit although the manoeuvring performance and propulsion system performance are only satisfactory. The length of the parallel midbody restricts the manoeuvrability in high ice concentrations. The AC/AC system on this ship has had initial reliability problems and ongoing maintenance problems and the system is considered too complex. Even in the first year ice the master is careful to protect the propellers and rudder by operating cautiously. As the ship is able to refuel more frequently, maintaining the draft is not a concern in Gulf operations.

The reference transit for the Earl Grey is in the Gulf of St. Lawrence in winter. The ship has much more power than the previous ships that the master has commanded. No performance components are troublesome.

The reference transit for the Arctic is a year round consideration of the ice types encountered on all the voyages and of the long open water segments. The major considerations are:

- manoeuvrability to avoid ridges and multi-year ice. This

is difficult because of the length of the parallel midbody.

- pressured ice as the ship has no reserve power in heavy ice conditions.

- strength of the ship in multi-year ice collisions and longitudinal strength in open water for severe pounding due to the flare forward. The lack of strength also causes vibration and springing.

- performance in heavy ridging in high friction conditions as the ship has relatively poor astern performance in broken channels.

The reference transit for the Oden is a trip from the Baltic to the ice off the east coast of Greenland. This trip involved exposure to North Atlantic storm conditions. The ship is rated good or excellent for all components of transit performance. She is judged to have better seakeeping than most icebreakers in Atlantic conditions. In heavy seas, spray is an operational concern and the ship received some damage forward from shipping green water. In open water the ship is not economical at high speeds. In Baltic transits the Oden is better than the immediately preceding generation of ships in all aspects of transit performance except level ice, broken ice and open water where she is ranked equal.

The reference transit for the Kontio is in the Baltic where she is able to maintain an average sped of 10 knots. She received good or excellent rankings for all components of performance except open water performance. She is judged to better than the older generation of ships in all components except open water performance. In open water the seakeeping performance is not satisfactory and she squats significantly in shallow water. In open water the ship is not capable of running on one engine and hence tends to be uneconomical at low speeds.

3.6 Comparison of Phase 2 and Phase 1 Ships

3.6.1 Introduction

As described in section 7 of Appendix B, masters of the ships in the phase 2 study compared their ships with other ships in the phase 2 study and with ships in the phase 1 study. Similarly masters of the ships in the phase 1 study compared their ships with both phase 1 and phase 2 ships. In general there was good agreement between the evaluation of a ship by its master and the evaluation of that ship by an other master. Differences arose primarily because of the different emphasis used as a basis for the evaluation. As an example the master of the St. Laurent judged the propulsion system on the MacDonald better than on his own ship, whereas the MacDonald's master judged the St. Laurent's better. In the former case, the system was judged superior due to the better fuel consumption of the

MacDonald compared to the St. Laurent. In the latter case, the system was judged better due to the St. Laurent's greater power. Similarly the masters of the phase 1 and phase 2 ships had different biases when evaluating each others ships. The masters of the phase 1 ships emphasized their own mission roles of ice management, supply and anchor handling (for drillships or platforms) in severe conditions with multi-year ice present. These are conditions in which the Canadian Coast Guard ships would have difficulty operating. In addition the CCG ships are not equipped or designed to perform these missions. The phase 2 masters emphasized their primary mission of ice escort which the Beaufort Sea ships could not perform efficiently primarily because of their poor astern performance and for some of the ships because of their poor manoeuvrability. Nevertheless there was good agreement on performance trends.

The design features of the ships in phase 1 and phase 2 complement each other. Features on the phase 2 ships were not available on the phase 1 ships. Examples include triple screws, AC/AC propulsion systems and an interim heeling system (run by compressed air) on the phase 2 ships. Certain features were present in each phase, including square sterns, reamers, bubblers and nozzled propellers. Other features such as the bows extended the range of shapes from the very high flare angles of the Robert Lemeur's bow to the very low flare angles of the St. Laurent and MacDonald.

An overview of the key considerations for the design features as learned from the phase 1 and 2 interviews is discussed in the following sections.

3.6.2 Bow Shape

The bows in the phase 2 study extend the range of shapes to those with very low flare angles (St. Laurent and MacDonald). These ships confirm the trend shown in phase 1 that the ships with high flare angles have difficulty in breaking out of a channel. The ships with high flare angles exhibit the same tendency as those with very low flare angles; lack of directional control. The Arctic and Oden with the highest flare angles in the phase 2 study pound in extreme open water conditions in a similar fashion to those ships in phase 1.

The ships with icebreaking bows and low freeboard are wet in severe open water conditions. Higher freeboards help to reduce wetness, although the fitting of a forecastle has not cured the tendency on the R class. The ships in phase 2 which have been optimized more for open water service (Black and Grey) are good in rough open water.

3.6.3 Bow Stopper

Unlike the ships in the phase 1 study, the majority of the ships in this study rarely engage the bow stoppers. The stoppers in phase 2 (with the exception of the 1100 class and the

Oden) are relatively small and are deeply immersed. The ships in phase 1 are used aggressively in the ice defence role attacking large ridges and old floes. The stopper on the 1100 class confirms the findings in the phase 1 study. If the wedge is too far forward and too close to the waterline it prevents good ridge penetration and may interfere with the flow of broken ice. In addition, if the shape is too blunt the deceleration in ridges is high. The stopper/wedge on the Oden confirms the ability to clear ice to the side leaving less ice in the wake.

3.4.4 Reamer

The reamer on the Oden confirms the findings in the Phase 1 study. The reamer reduces the resistance along the ships side in the ahead mode in a number of situations (level ice, ridges, broken ice, pressure etc.). Astern it can add to the resistance (particularly in pressure) and forces the operator to widen the path through ridge. When manoeuvring it provides room for the stern to swing and overcomes the negative effects associated with long parallel midbodies on manoeuvring ability.

3.4.5 Length of Parallel/Shape Midbody

The larger icebreakers in the phase 2 study all have short midbody lengths (with the exception of the Oden) and manoeuvre well. The Oden with the reamer, heeling and a narrow stern manoeuvres very well. The ships with the longer midbodies (Arctic, Grey and 1100 class) have the same difficulties in manoeuvring as the ships in the phase 1 study with long midbodies and no reamers.

Unlike the ships in the phase 1 study, most of the ships in the phase 2 study have long transitions from the bow to the midbody. These shoulder areas are characterized by low flare angles and hence high wedging forces. It is these areas at which the ships tend to stick in heavy ridging and thick ice.

3.4.6 Sloped Midship Sides

Even with the slopes of up to 12 degrees in the phase 2 ships there was no noticeable effect of the slope on performance, other than the tendency to wedge in ridges as noted on the Kontio or to not wedge as noted on the Polar Star. The slope was thought to be useful in keeping ice off the deck in extreme pressure. This confirms the observations in the phase 1 study.

3.4.7 Stern Shape and Propeller Arrangement

The stern shapes of the four major CCG icebreakers are similar to the bows and they are effective in breaking ice and allowing the ships to manoeuvre astern. Although the sterns of the Polar Star and the Arctic are similar to the CCG ships, the concerns about damages to the propellers on the Star and to the

steering gear system on the Arctic prevent the ships from being used to their full capacity astern. This contrasts to the experience on the phase 1 ships where the main impediment to astern performance was the square sterns which pushed ice and prevented astern icebreaking and manoeuvring. Four ships in the phase 2 study have sterns which inhibit astern performance; the Martha Black with a transom stern (in Arctic conditions), the Earl Grey with a square stern, the Oden with a wide stern with icebreaking shape but with iceknife/rudder stops close to the surface and the Kontio with an undercut and relatively flat sections. The Kontio exhibits a similar lack of directional control astern as the Kigoriak

Except when operating well beyond their ice class, the ships in the phase 1 study had little propeller ice interaction ahead. These ships had various combinations of nozzles, generous hull/propeller clearances and hull shapes which protected the propellers. Similarly the nozzled propellers of the Oden coupled with the bow wedge and the stern shape minimize the amount of interaction. Two of the ships in the phase 1 study, the Martha Black and the Polar Star have a considerable amount of propeller/ice interaction ahead particularly when manoeuvring. The outboard propellers on both ships are not well protected by the hulls and the hull forms feed ice into the propeller planes.

Unlike the ships in the phase 1 study, the nozzled ships in the phase 2 study (Arctic, Grey and Oden (Baltic only)) suffer from little or no blockage. On the Arctic this can be attributed to the deep immersion of the nozzle and the lack of aggressive backing. On the Grey, the ship operates astern infrequently as she has a large reserve of power for operation in the first year ice conditions in the Gulf of St. Lawrence. In Arctic operations when the Oden is operated aggressively blockage occurs more frequently.

Three of the ships in the phase 2 study have 3 propellers; Polar Star, Louis S. St. Laurent and John A. MacDonald. This allows the master to maintain thrust on the centre screw in the desired direction while using the differential thrust of the wing screws to manoeuvre. This is particularly advantageous astern when the rudder is centred to avoid damage. The capability gives the triple screw ship an advantage over twin screw ships when backing down and manoeuvring around a beset ship. In fact in heavy ice the twin screw ships are not able to manoeuvre astern as all the thrust is required to maintain astern way. As in phase 1, the single screw ships are at a disadvantage when backing as they have no manoeuvrability. In both phases, the twin screw ships with the propellers close to the centreline do not have the same amount of differential thrust as those with the propellers more widely spaced.

3.4.8 Propeller Type

All of the ships in the phase 1 study had controllable

pitch propellers, with four of the five having nozzles. In phase 2 four ships have controllable pitch propellers, three with nozzles. The rest of the ships in phase 2 have fixed pitch propellers. The masters of the ships with nozzles are less concerned about multi-year ice than the masters with the open propellers. Of the two ships with open CP propellers (Polar Star in phase 2 and Terry Fox in phase 1), the master of the Star is more concerned about ice interaction because the propellers are relatively weak and are not as well protected by the hull. All of the masters with fixed pitch propellers who operate in the Arctic are concerned about propeller interaction with multi-year ice particularly when backing and when changing the direction of the propeller when the ship has way on. The five breakages of the Martha Black's fixed pitch propellers in two seasons and the damage to the Cornwallis's blade show that propellers with relatively light scantlings have no place operating in multi-year ice. In thick ice such as deep ridges the open propellers have less thrust degradation than the nozzled propellers.

3.4.9 Rudders

With the exception of the Arctic and the Cornwallis, all of the ships have few concerns about the strength of the rudder and steering system when operating in ice. Due caution is exercised when backing in heavy ice by all the masters, with a greater concern about this manoeuvre by the phase 2 masters.

The rudders in the wake of a propeller are more effective than the single rudders on twin screw ships. The extreme example of this is the 15 second delay in response to a helm order on the Radisson.

3.4.10 Propulsion Control

As the propulsion control system does a good job of protecting the machinery of all the ships in both phases, the major issue is the full ahead/astern thrust time. For the majority of the masters this should ideally be about 10 to 12 seconds. The masters of the ships with the electric drive (all in phase 2) are more likely to have this time. Slow times increase the risk of getting stuck when ramming. In addition they require the master to anticipate events, which slow down the operation as he tends to operate conservatively to avoid damage. The exception to the preceding is the master of the Polar Star who is reasonably satisfied with 40 seconds. This ship has the highest power to displacement ratio of any of the ships in both phases and is operated conservatively because of the risk of damage to the propellers.

3.4.11 Thrusters

With the exception of open leads, none of the masters with conventional thrusters in both phases use the thrusters in ice. The bubbler used as a thruster is less effective than a conven-

tional thruster of equal power. It does however have the advantage of acting as a fender when approaching piers or other ships.

3.4.12 Friction Reduction Auxiliaries

The bubbler systems (if operative on the Arctic) are used in heavy ice with high friction conditions. They only have a net benefit in these conditions. The master of the Larsen tends to use the bubbler in most ice conditions as it leaves less ice in the wake which makes it easier for the escorted ship to follow. In addition with a clearer wake it makes it easier for the icebreaker to back down. The bubbler on the Kontio does reduce the amount of ice in the track and reduces the amount of propeller/ice interaction. Because of the high power consumption it tends to only be used in severe conditions and as a thruster to aid the manoeuvring astern. The water wash systems are more likely to be used on a univer[illegible] basis to reduce friction under all conditions as they have l[illegible]ower consumption.

3.4.13 Heeling System

In ice, the active systems (with times of about 2 minutes) are used for extraction, primarily in ridges, in both phase 1 and phase 2. The system on the MacDonald with a time of 10 minutes is too slow. With the exception of the Polar Star, Radisson, Kontio and Oden they are not used in other ice conditions. The systems on the Oden and Kontio are used in the cycling mode to enhance the performance in severe conditions such as high friction and rubble fields. The Intering system on the Larsen is not used in ice. The passive Flume system on the Black is used in ice as the enhanced rolling when the system is at working level helps the passage through level and broken ice.

In open water, the Flume systems fitted to the ships in phase 2 are effective in reducing the roll but the round bilges of some of the ships still give unacceptable rolling. The Intering system on the Larsen is effective in reducing the roll. Although non of the ships in phase 1 have Flume systems the rolling is far less violent as the ships all have full bilges with chines. The midship shape of the Oden exhibits similar roll damping tendencies to the hulls of the phase 1 ships.

3.4.14 Hull Coating

In both phases, the masters agree that an effective, intact coating is essential for all aspects of icebreaking. A low friction surface on the Kontio is achieved by a stainless steel band at the waterline.

3.5 Conclusions

The conclusions fall into three categories:

1) The validity of the questionnaire process
2) The role of the design features in the determination of vessel performance
3) The ability of the various vessels to perform their assigned mission roles

3.5.1 Questionnaire Process

The questionnaire has proven its worth, as valuable qualitative information about vessel design features and the ability to perform the mission roles was obtained. This information complements and supports the full scale results. Allowing for the bias of the masters related to their own operational background, there was good agreement on the role of the design features for one ship when evaluated by different masters. This enables a valid comparison of the features of different ships.

3.5.2 Role of Design Features

The qualitative assessment of the role of the design features on performance is summarized in the following subsections. Conclusions from the phase 2 study which extend the range of understanding about design features found in the phase 1 study, incorporate the results of both studies. Results unique to the phase 1 study are not repeated.

Bow Shape:

- all the bows are effective in level ice in the ice conditions and thicknesses in which they operate. Quantification of the effectiveness is from full scale trials.
- bows with a moderate V shape offer good directional stability in both level ice and ridge breaking
- bows with very high or very low flare angles have poor directional control. The ships with high flare angles are able to break out of channels readily, whereas those with low flare angles are not.
- bows with near vertical stem profiles push ice ahead of the vessel.
- the bows of the major icebreakers are less than ideal for extreme open water conditions. The bows with high flare angles and shallow stem angles tend to pound. The bows with low flare angles but little above water flare are wet. On deck wetness can be reduced by providing adequate freeboard. Flat near horizontal forefoot sections will cause slamming.

Bow Stopper:

- deeply immersed small stoppers rarely contact solid unbroken ice.

- blunt angle stoppers with vertical profiles cause high decelerations in ridges
- if the stopper is too far forward and close to the waterline, the vessel is stopped before the maximum vertical icebreaking force can be developed. In addition the stopper may trap floes and carry them along with the ship.
- wide deep wedges are effective in clearing ice from the wake. The effectiveness is reduced at higher speeds.

Reamers

- are effective in reducing midbody friction
- assist in manoeuvring by providing space for the stern to swing, but the reamer width must be considered in conjunction with the length of parallel midbody.
- increase the resistance astern, particularly in pressure

Length and Shape of Parallel Midbody:

- excessive length compromises manoeuvring and increases the friction in pressured ice and ridges
- large diameter bilges cause large amplitude rolling which is uncomfortable even with the reduction from a passive flume stabilization system
- long transitions from the bow to the midbody with low flare angles cause the ship to stick in thick ice and heavy ridging
- midship flare angles up to 12 degrees are not observed to have any significant effect on performance. They may be useful in preventing ice from coming on deck in high pressure.
- vertical ship sides are not observed to have any detrimental effect on performance

Stern and Propeller Arrangements:

- the astern performance of those ships with square or transom sterns is generally poor
- stern cutaway and flat sections aft cause poor astern directional control in thick ice on single or twin screw ships
- sterns with less beam than midship and with suitable lines to allow the ice to rise clear of the propellers minimize the amount of propeller ice interaction. This must be designed in conjunction with an ice clearing bow and midship section.
- the sterns with icebreaking shapes similar to the bow shapes break ice and manoeuvre well astern
- clearance above the propeller is essential to minimize the ice/propeller interaction
- nozzled propellers protect the propeller from interaction with large pieces of multi-year ice, but performance may be degraded by blockage. Deep nozzle immersion can reduce propeller ice interaction

- open propellers are effective in conditions with a great ice thickness (ridges, broken or pressure ice) as they suffer from less thrust degradation than nozzle ships. However, in multi-year ice, due caution is exercised by the masters in order to prevent damage. Open fixed pitch propellers risk damage when the propeller stops when the thrust direction is changed and the ship is still underway.
- weak propellers are unsuited for operation in multi-year ice and compromise the ability of the vessel to perform assigned mission roles or reduce the effective performance
- propellers which are not well protected by the hull have significant ice interaction. This limits manoeuvring and astern performance.
- a rudder is most effective behind a propeller. Single rudder, twin screw ships can have significant lag in helm response which may cause erratic course keeping in broken ice.
- weak steering gear systems compromise the astern capability of the ship
- single propellers, although less vulnerable due to their centerline location, do not permit astern manoeuvrability
- triple screw ships have good manoeuvrability when using differential thrust, particularly astern when the rudder is centred

Propulsion Control

- a full ahead/astern thrust time of 10 to 12 seconds is required for aggressive icebreaking to minimize the risk of getting stuck in ridges and for fast response to avoid damage.

Auxiliaries for Friction Reduction:

- the bubbler is economical when operating alone only in limiting conditions (i.e., thick ice and low speed and high friction conditions)
- the bubbler will decrease the amount of ice in the track and reduce the amount of propeller/ice interaction
- the bubbler can act as a fender
- the bow water wash system is universally effective in friction reduction

Heeling System

- active heeling systems with times of less than 5 minutes are used for extraction from heavy ridging. This occurs infrequently with a good low friction hull coating.
- active systems are useful in extreme conditions such as rubble fields and high friction on a continuous cycling basis
- flume passive systems or Intering systems are effective

in reducing severe rolling in open water, but on vessels with large bilge radii the rolling is still uncomfortable.
- heeling the ship can produce significant reductions in turning diameter but if the system is to be used the time to heel the ship must be in the order of 2 minutes

Hull Coating:

- an effective, intact coating is essential for effective icebreaking
- a stainless steel band at the waterline is effective in friction reduction

3.5.3 Mission Roles

The ships in the study have rarely operated beyond their design ice class while performing their main mission roles. With the exception of the Martha Black performing the ice escort role in Arctic summer ice, all have been able to perform their assigned main mission roles despite deficiencies in some aspects of performance. The captains have capitalized on the vessels' superior aspects of performance to overcome the deficiencies. In the ice escort role in heavy Arctic summer ice the Martha Black has no superior aspect of performance and hence runs out of options. In the Gulf of St. Lawrence the sistership of the Martha Black, the Edward Cornwallis, is able to perform the escort role well. Recognition of the environmental conditions in which the ship will operate and designing features to deal with this environment are very important for the success of the mission. The vessel designs have not been compromised to perform minor roles such as SAR and hence the vessels are not able to perform these roles efficiently. In most cases, a compromise would reduce the efficiency while performing the primary role and would be unacceptable.

Table 3.1

Ship Missions and Operational Areas

Ship	Missions	Area/Time Operation
Polar Star	Ice Management Ice Escort Research/Supply SAR	Antarctic/Spring Eastern and Western Arctic/Spring to Fall
Louis S. St. Laurent	Ice Escort Ice Management SAR Supply	Eastern Canada/ Winter Arctic/Summer
John A. MacDonald	Ice Escort Ice Management SAR Supply	Eastern Canada/ Winter Arctic/Summer
Pierre Radisson	Ice Escort Ice Management Supply SAR	St. Lawrence and Gulf/ Winter Arctic/Summer
Henry Larsen	Ice Escort Ice Management SAR	Gulf of St. Lawrence/Winter Arctic/Summer
Martha Black	Buoy Handling Ice Escort Supply SAR	Western Arctic/ Summer
Edward Cornwallis	Ice Escort Buoy Handling Supply SAR	Gulf of St. Lawrence/Winter
Earl Grey	Buoy Handling Ice Escort Ice Management SAR	Gulf St. Lawrence /Winter
Arctic	OBO Cargoes	Eastern Arctic/ Late Spring to Late Fall

Table 3.1 continued

Oden	Ice Escort	Baltic/Winter
	Ice Management	Arctic/Summer
	SAR	
Kontio/Otso	Ice Escort	Baltic/Winter
	Ice Management	
	SAR	

Table 3.2

Ship Masters and Their Icebreaking Experience

Ship	Master	Other Ships
Polar Star	R. Hammond	Glacier
St. Laurent	M. Tanner	MacDonald
MacDonald	J. Barry	St. Laurent Polar Sea Kalvik
Radisson	P. Toomey	Mudyug Kalvik
Larsen	S. Gomes	MacDonald
Martha Black	R. Mellis	Bernier Camsell Radisson
Cornwallis	L. Meysner	MacDonald
Earl Grey	R. Southin	Gilbert Grenville Cabot
Arctic	D. Millar	Arctic (old bow)
Oden	A.Backman	Tarmo Ale Ymer
Kontio	R. Rintala	Urho Apu

TABLE 3.3

Performance Categories and Design Features

Performance Categories	Design Features
Level Ice	Bow Shape
Ridges	Bow Stopper
Broken Ice	Reamer
Manoeuvring	Length of Parallel Midbody
Pressured Ice	Slope of Midship Sides
Transit	Stern Shape
Propulsion System	Propeller Arrangement
Open Water	Propeller Type
Rudders	
Propulsion Control	
Bow and Stern Thrusters	
Friction Reduction Auxiliaries	
Heeling System	
Hull Coating	

TABLE 3.4

OVERALL PERFORMANCE BY CATEGORY

1+ EXCEPTIONAL 1 GOOD 0 ACCEPTABLE -1 DEFICIENT -1- UNACCEPTABLE

PERFORMANCE CATEGORY	POLAR STAR	ST. LAURENT	MACDONALD	EARL GREY	ARCTIC
LEVEL ICE	1+	1	1	1+	1
RIDGES	1	1	1	1+ TO 1	1
BROKEN ICE	1+	1	1	1+ TO 1	1
MANOEUVRING	1+	1	1	1 TO 0	0
PRESSURE	NO RANKING	0	1	1 INDEPENDENT -1 ESCORT	0
PROPULSION SYSTEM	1	1	1	1	1
OPEN WATER	0	1 CALM -1 SEVERE	0	1	1

PERFORMANCE CATEGORY	RADISSON	LARSEN	MARTHA BLACK	CORNWALLIS	ODEN	KONTIO
LEVEL ICE	1	1+	1 0.6 M ICE 0 - -1 M ARCTIC	1+	1+	1 TO 0
RIDGES	0	1	0 TO -1	1	1	1
BROKEN ICE	1	1	0	1	1	1
MANOEUVRING	0	1	0	1	1+	1
PRESSURE	0	1+	-1	0	1 MINIMAL EXPER	1
PROPULSION SYSTEM	1+ TO 1	1	1	0	1+	1
OPEN WATER	0 MAJORITY -1 SEVERE	1	1	1+	1	-1

TABLE 3.5

ABILITY OF SHIPS TO MEET MISSION ROLE

1+ EXCEPTIONAL 1 GOOD 0 ACCEPTABLE -1 DEFIENCT -1- UNACCEPTABLE

MISSION	POLAR STAR	ST. LAURENT	MACDONALD	EARL GREY	ARCTIC
ICE MANAGEMENT	1+	1	1	1	LIMITED 1
TOWING	0	NA	1	NA	NA
BOUY HANDLING	NA	NA	NA	1	NA
ICE ESCORT	1+	1	1	1	NA
SUPPLY	1	NA	1	NA	CARGO MISSION BULK 1, TANKR 0
SAR	1	0	0 TO -1	1 TO 0	NA
TRANSIT	1+	1	0	1+ TO 1	1

MISSION	RADISSON	H. LARSEN	MARTHA BLACK	E. CORNWALLIS	ODEN	KONTIO
ICE MANAGEMENT	1	1	NA	1	1	1
TOWING	NA	NA	0	0	1+	0
BOUY HANDLING	NA	NA	1	1+	NA	NA
ICE ESCORT	1	1	0 TO -1	1	1+	1
SUPPLY	0	0 LIMITED	1+ TO 1	0	NA	NA
SAR	0	1	1+ TO 1	0	1+ *	-1
TRANSIT	1	1	1	0	1	1

* RATING IS IN ICE

4.0 LEVEL ICE PERFORMANCE AHEAD

4.1 General

In Phase 1, Icebreaker Design Synthesis - Analysis of Contemporary Icebreaker Performance, reported in TP 9992E [91], both analysis and comparison of level ice performance was reported for all vessels as a group in the following sequence of performance categories.

* Full power performance, speed versus ice thickness.
* Power versus ice thickness at constant speed.
* Propulsive performance.
* Resistance versus ice thickness at constant speed.
* Influence of hull lubrication systems.
* Influence of hull condition and season.

Reporting in this fashion was convenient since the ship trials had been carried out, analysed and reported in the source documents for that study, in a predominantly standardised manner. This is not the case for this current study, where there are many differences between the format of ship trials, analysis and reporting for different vessels. Data selection and method of analysis is therefore tailored to the available trials data for individual vessels. Consequently, the clearest manner of reporting the analysis is to deal with each vessel individually, following which the results for all vessels are then summarised and compared.

Analysis of the level ice performance categories for individual vessels is described in detail in Sections C 4.5.1 to 4.5.12 of Appendix C.

The vessels or vessel classes are reported in the following sequence.

* M.V.Arctic-Old
* M.V.Arctic-New
* Polar Class
* R-Class
* Louis S. St.Laurent
* Polarstern
* Mudyug-Old
* Mudyug-New
* Type 1100
* Bay Class
* Otso Class
* Oden

The results of the level ice performance data analysis for all vessels are then summarised and compared for individual performance categories in Sections 4.2 to 4.6 below. The influence of hull condition and season upon level ice performance is not dealt with in this Chapter. These influences are combined in a complex manner with those of hull form and features and

are subsequently addressed in the overall analysis of level ice performance in Chapter 11.

In the Phase 1 project, the ship trials were separated into two distinct groups on the basis of environmental and ice conditions. These two groups were designated Winter and Spring/Fall Beaufort Sea conditions. Differences in overall environmental conditions within each group were small, especially for the more numerous and important Winter trials, which received detailed analysis. Comparison between the performance of vessels and analysis of the influence of design features on performance was then carried out without the need to correct data for the influence of different trials conditions.

In this project, however, the range of environmental conditions is varied and large, both between trials for different ships and often between trials for the same ship. Consequently, comparisons between the performance of the vessels in those categories which are particularly sensitive to environmental conditions, such as level ice resistance, cannot be made readily without considering the associated environmental data. These environmental data are reported in Chapter 2. They are brought together with the ship resistance data from Section 4.5 and ship parameter data from Chapter 2 in an overall analysis for level ice performance in Chapter 11.

4.2 Full Power Performance, Speed versus Ice Thickness

4.2.1 Results

The level ice performance data in Appendices C 4.5.1 to C 4.5.12 and open water performance data in Appendix Tables C 7.2 to 7.12 have been used to construct plots of ship speed versus level ice thickness at full power ahead for all vessels in the group. These plots are given in Figures 4.2.1 and 4.2.2.

It was demonstrated in Phase 1 that the typical speed versus level ice thickness relationship at constant power is essentially linear. The best linear fits to the data, up to the maximum ice thicknesses in individual trials, are therefore shown in Figures 4.2.1 and 4.2.2. Associated shaft powers and ice flexural strength indices are given.

It will be noted that individual ship trials have been carried out in a wide range of maximum ice thicknesses relative to the limiting ice thickness capabilities of the vessels. M.V.Arctic-New, for example, has been tested close to its limiting ice thickness in the prevailing strength of ice, while Oden has been tested to only 40% of its probable limiting ice thickness. Taken overall, vessels in the group have been tested to an average of two thirds their limiting ice thickness, which is similar to the experience in Phase 1.

It must be understood that the data are specific to the

different environmental and, in some cases, hull conditions at the time of the trials. Consequently, the data can only be used to compare the performance of different vessels in a very limited and cautious manner.

For example, an indication of the effect of ice strength upon performance can be noted by considering the R-Class data for trials in weak ice with Pierre Radisson, versus in strong ice with Radisson and Franklin, all at similar powers. When the performance lines are extrapolated to a common speed of 1 m/s, the effect of decreasing ice strength from approximately 500 to 150 kPa, is an increase in ice thickness capability of approximately 32%. This is very similar to the equivalent Phase 1 difference in performance in Winter and Spring ice.

Further, the effect of the new bow on M.V.Arctic can be assessed in an approximate fashion. At 1 m/s, the new M.V.Arctic will break 46% more ice of slightly greater strength than the old Arctic.

However, a similar level of comparison of the icebreaking capability of the R-Class relative to M.V.Arctic-Old and New cannot immediately be made since the ice conditions do not match and the hull conditions on the trials were very different.

The above examples illustrate the due caution which must be exercised in comparing the speed versus level ice thickness data presented.

A number of formulations have been developed in the past, including the Phase 1 project, whereby an attempt might be made to correct the data in Figures 4.2.1 and 4.2.2 to a common base of ice and hull conditions. However, none of these formulations is applicable to the combinations of environmental and hull conditions found in this extensive Phase 2 data set. Investigation of these effects beyond that attempted so far has therefore become of equal neccessity and importance in the project as the influence of design parameters and features. This investigation is addressed in detail in the overall analysis of level ice performance in Chapter 11.

Manoeuvring tests, reported in Chapter 6, were largely carried out in association with the level ice performance trials. Figures 4.2.1 and 4.2.2, therefore provide directly a measure of the vessels' icebreaking capabilities during the manoeuvring trials. Extrapolated values of level ice thickness at 1 m/s are used from the Figures in order to bring level ice thickness for individual turning tests to a common data base.

4.2.2 Conclusions

Speed versus level ice thickness data at full power ahead have been determined for all vessels in the Phase 2 group. These data apply for the specific environmental and hull condi-

tions at the time of the various ships' trials. Since these conditions vary widely, the data can only be used to compare the performance of different vessels in a very limited and cautious manner.

There is no commonly accepted method of adjusting the performance data to a common environmental and hull condition base. This consequently becomes of equal neccessity and importance in the project as the influence of design parameters and features.

The data confirm the finding in the Phase 1 project that the level ice thickness which can be broken by a vessel in weak Spring ice is approximately one third greater than in Winter strength ice.

The data are in a form which is directly applicable to bringing the manoeuvring performance data in Section 6 to a common ice thickness format.

4.3 Power versus Ice Thickness at Constant Speed

4.3.1 Results

Power versus ice thickness data for all trials of all vessels, except for the Otso Class for which trial powers are not reported, are given in the Appendix Table C4.3 for ship speeds of 1,2 and 3 m/s. The data are a function of the level ice resistance data in Table C4.5 and the propulsive performance data in Appendix C4. As in Phase 1, shaft power has been corrected linearly with respect to beam to the common beam of Kigoriak (19.25m). No corrections have been made for environmental and hull conditions.

The data are plotted in Figures 4.3.1 and 4.3.2 for 1 m/s, Figures 4.3.3 and 4.3.4 for 2 m/s and Figures 4.3.5 and 4.3.6 for 3 m/s. For each speed, the data are split into two groups, one with ice flexural strength index of less than, and one greater than 300 kPa.

As in the case of speed versus level ice thickness above in Section 4.2, the power versus level ice thickness data can only be used for comparative purposes in a very limited and cautious manner. Nevertheless, some general relationships which might be expected, especially in the light of the Phase 1 findings, can be noted.

In Figures 4.3.2, 4 and 6, the data from separate trials of the virtually identical vessels, Radisson and Franklin, in similar high strength ice, are virtually identical.

Again, in high strength ice at slower speeds where ice-breaking predominates, the thickness exponent for the contemporary vessel Mudyug-New is considerably lower, in keeping with

the results for Phase 1, than for the conventional R-Class as well as for other conventional vessels in the lower strength group.

Moreover, in the lower strength ice, it is noted that the powering performance curve for the Polar Class lies logically between those for M.V.Arctic-Old and New, as might be expected when its hull angles (Table 2.3) and trials ice strength lie between the two.

The powering data therefore provide an indication that logical trends lie within the data group. However, they cannot be determined directly from the graphical presentations for several reasons.

Firstly, the data include the effect of different propulsion systems which must be separated as in the Phase 1 analysis, such that comparisons between ice resistance can be made.

Further, for many vessels, each trial yields data for only one ice thickness, which is often significantly different from other ice thicknesses in the data set.

Additionally, the data include the effect of both different hull forms and different trials ice conditions and hull conditions.

It is therefore clear that the analysis for the effect of hull form parameters and features upon performance in level ice must be carried out using ice resistance data, and must also be carried out concurrently with the determination of the effect of environmental and hull conditions. This demands a more sophisticated analysis than is possible using simple graphical presentations alone.

Level ice resistance data are analysed and presented in Section 4.5 below and the concurrent analysis of all parameters influencing the data is reported in Chapter 11.

4.3.2 Conclusions

Power versus level ice thickness data at constant speeds have been presented for all trials of all vessels in the Phase 2 group. These data apply for the specific environmental and hull conditions at the time of the individual trials. Since these conditions vary widely, the data can only be used to compare the performance of different vessels in a very limited and cautious manner. Nevertheless, it is possible to determine some general and logical relationships within the data set.

The powering data include the effect of different propulsion systems. Therefore, in order to determine the effect of hull form parameters and features upon performance, level ice resistance data must be used. Furthermore, the analysis must deal concurrently with all significant environmental, hull form

and hull condition variables.

4.4 Propulsive Performance

4.4.1 Analysis

Propulsive performance has been analysed in Appendix C in the form of net propulsive thrust per unit shaft power (specific net thrust), and is presented in the units of Newtons per Watt (N/W).

Net propulsive thrust (or total resistance) is the total propulsive thrust - shaft thrust for open propellers and shaft-plus-duct thrust for ducted propellers - less the thrust deduction.

Thrust deduction is derived from model tests for the following vessels:

M.V.Arctic-Old and New
R-Class
Otso Class
Oden

from full scale propulsion overload tests for

Polar Class;

and reasonable assumed values, relative to the hull form and propulsion arrangement, are used for

Louis S.St.Laurent
Polarstern
Mudyug-Old and New
Type 1100
Bay Class.

In all cases, the thrust deductions are open water values. That is, no allowance is made for the possibility that thrust deduction on the trials might be altered due to the flow around the hull and into the propulsion system being that of a mixed water and ice medium. If this were the case, both level ice resistance (except that measured directly for Mobile Bay), as given in Section 4.5, and Specific Net Thrust given in this section, would require correction. However, no such correction if justified can be made, since the full scale influence of ice upon open water thrust deduction, has as yet to be determined.

Moreover, as ice passes through a propulsion system, additional power, over and above that required to generate the necessary thrust, is used in ice milling. This additional power serves to reduce specific net thrust relative to ice-free conditions and is inherent in the specific net thrust values derived from the trials data. A possible difficulty presented

by this effect lies in the comparison of propulsive performance derived from vessels' trials in significantly different ice thicknesses relative to their size.

For the most part, however, the Phase 2 group of vessels were tested in ice conditions which did not result in significant levels of propeller and ice interaction. The highest level of interaction occured for Polar Sea in 1.74m of ice in McMurdo Sound. This ice was, however, relatively weak, which one would expect to limit its effect upon power. Another case is that of Franklin in the second Lake Melville trials in relatively thick ice and snow. In Appendix C 4.5.4, it is noted that propulsive performance derived from this trial appears to be slightly lower than that derived from other R-Class trials in lighter ice.

The relative magnitude of ice milling power to thrust power is a subject which has to date received very little attention. Limited studies have shown that in thick, strong ice, average milling power might be of the order of 10% of thrust power. Such conditions are, however, well removed from those in the Phase 2 trials and it is judged that, although the effects of some relatively different levels of interaction are present in the propulsive performance results, the numerical level of these effects are unlikely to be significant. For the most part, the specific net thrusts should be close to ice-free values.

The analysis of propulsive performance described above for this study is the same as that employed for the previous Phase 1 study.

Specific Net Thrust is analysed and presented in Appendix C as a function of both shaft power and ship speed. Comparisons are also made with specific net thrusts determined in Phase 1 for open propellers (Kalvik/Terry Fox) and ducted propellers (Kigoriak/ Robert Lemeur). As stated in the text, these comparisons are not entirely meaningful in absolute terms, since the size and power of the propulsion systems vary considerably. The comparisons are used principally as a reference to assist in construction of constant speed, specific net thrust curves through the data points.

The overall most meaningfull form of presentation and comparison of the specific net thrust data for the different vessels is one which includes the ship performance design condition. For icebreakers, this normally corresponds to the maximum power condition, again normally at bollard. The specific net thrust data described in Appendix C are therefore presented in this form in Figures 4.4.1 and 4.4.2.

4.4.2 Results

Ducted Propulsion

Figure 4.4.1 presents specific net thrust versus ship speed at maximum shaft power for the ducted screw vessels Kigoriak, M.V.Arctic, Polarstern and Oden. All propellers have controllable pitch.

It is noted that Kigoriak and M.V.Arctic have very similar characteristics at all speeds, with M.V.Arctic data being some 6% lower than those for Kigoriak. Oden data are an additional 4% lower than M.V.Arctic at bollard, increasing to 23% lower at 6 m/s. Polarstern data are 9% lower than Oden at bollard but similar at 5 m/s.

There are numerous possible reasons for the differences seen in the magnitude and nature of the specific thrust curves. These include propeller design type and scantlings, intensity of loading, differences in hull and propulsion interaction and unusual design requirements. Detailed investigation of these possible causes is a major undertaking and well beyond the scope of this project. However, these factors are investigated at a practical working level below.

The intensity of propulsion loading at maximum power and bollard is given below for the four vessels. Propulsion loading is given in terms of bollard pull in tonnes per unit propeller disc area in square metres.

Vessel	Propeller disc loading tonnes/ m^2
Kigoriak	8.26
M.V.Arctic	7.25
Polarstern	6.81
Oden	7.34

Abnormally high (or low) loading would normally result in a measurable decrease (or increase) in specific thrust. However, the loadings given above are within normal design ranges for ducted propulsion and have a maximum spread of 20%. Propeller loading intensity is therefore unlikely to be a significant cause for the differences in specific net thrust.

As stated in Appendix C 4.5.6, it is understood that Polarstern was designed as a research vessel for low propulsion noise characteristics. This is clearly a probable reason for its net specific thrust to be relatively low.

Differences in hull and propulsion interaction are also known to be present in Figure 4.4.1. As noted in Appendix C4.5.1 , M.V.Arctic has a slightly higher thrust deduction than Kigoriak, which accounts for most of the difference in specific net thrust.

Moreover, as noted in Appendix C 4.5.12, Oden has a higher than average thrust deduction at forward speed of between 0.27 and 0.32. This accounts for the decrease in specific net thrust with forward speed relative to that of Kigoriak and M.V.Arctic. Oden's thrust deduction at bollard of 0.11 is however normal, which leaves the lower specific thrust at bollard to be explained. The most probable reason is that of propeller and nozzle scantlings.

Oden is designed for unlimited operation in multi-year ice conditions, and as such the strength and therefore scantlings of the propeller and nozzle exceed all current regulatory requirements. On the other hand, Kigoriak was designed to CASPPR Class 3 requirements and M.V.Arctic to Class 2 requirements. It is entirely consistent that the difference in specific net thrust at bollard between Kigoriak/M.V.Arctic and Oden of 5-9%, could be the result of lower propeller and duct efficiency caused by higher scantlings. Propulsion losses also tend to increase slightly with increase in the number of propellers.

Oden's twin propellers relative to Kigoriak/ M.V.Arctics' single propeller could therefore be another contributory factor.

Open Propulsion

Figure 4.4.2 presents specific net thrust versus ship speed at maximum shaft power for the open screw vessels Terry Fox, Polar Class, R-Class, H. Larsen, Louis S.St.Laurent, Ann Harvey, Bay Class and Otso Class. Terry Fox and Polar Class have controllable pitch propellers. The remainder have fixed pitch propellers and electric motor drive.

It is noted that Terry Fox, R-Class and Ann Harvey have virtually the same specific net thrust at bollard, but that net specific thrust of the fixed pitch installations reduces, relative to that of Terry Fox's controllable pitch system, with increase in forward speed. Only bollard data are available for Louis S.St.Laurent and this agrees well with those for Terry Fox, R-Class and Anne Harvey. At bollard, Otso has a specific net thrust 7% lower than that of Terry Fox, but this then reduces with forward speed at a lower rate than for other fixed pitch installations of Ann Harvey and R-Class.

Polar Class data lie some 12% lower than Terry Fox at bollard and 20% lower at 6 m/s. In keeping with the controllable pitch characteristics for Terry Fox, the Polar Class curve does not reduce with forward speed as steeply as that for the fixed pitch vessels R-Class and Ann Harvey. The Bay Class have a specific net thrust at bollard some 8% higher than that of Terry Fox, but this reduces with forward speed at a much higher rate as noted for other fixed pitch installations. The Henry Larsen characteristics do not follow the trend of the other fixed

pitch vessels. Specific net thrust at bollard is 20% less than R-Class, its close sister vessel, but then reduces with forward speed at a considerably lower rate.

The probable reasons for the differences noted in the magnitude and nature of the specific net thrust curves in Figure 4.4.2 are discussed below.

The low values of specific net thrust for Henry Larsen, particularly at low speeds, are explained by an analysis in Reference 56. Compared with the performance of standard Troost "B" series propeller designs, the most commonly used in modern propeller design practice, the Henry Larsen propellers are shown to have a substantially poorer performance at bollard with no corresponding improvement in the free running condition. This is clearly confirmed in Figure 4.4.2, where specific net thrust in the free running condition at 8 m/s in only marginally higher than that for the R-Class and Ann Harvey, while bollard performance is substantially poorer. It is concluded that the Henry Larsen propellers are of a poor basic design.

The intensity of propulsion loading at maximum power and bollard is given below for the remaining seven open screw vessels.

Vessel	Propeller disc loading tonnes/ m^2
Terry Fox	5.00
Polar Class	8.78
R-Class	4.71
Louis S.St.Laurent	4.82
Ann Harvey	3.41
Bay Class	4.15
Otso Class	4.87

It is noted that the loading for the Polar Class is 76% higher than that of Terry Fox and even higher than that for the ducted screw vessels. This is considered the major reason for the Polar Class performance to be significantly lower than that of Terry Fox. Another but lesser factor, as discussed in Section 4.4.1 above, might be a higher level of propeller and ice interaction during the trials.

The intensity of loading for Terry Fox, R-Class and Louis S.St.Laurent are all similar and their specific net thrusts at bollard are all within 3% of each other. Their thrust deductions are also within 3% of each other. It is concluded that the propellers are all designed within good modern practice for the low speed icebreaking condition. Otso's slightly lower propulsive performance at bollard, but relatively improved performance at higher speeds, supports the concept that she is designed for relatively high ice and escort speeds in the limited thickness of Baltic ice.

The Ann Harvey has a loading 30% lower than that for Terry Fox and might therefore be expected to have a performance some 5% better, rather than identical. The probable reason is given in Reference 71, where it is noted that the Anne Harvey propellers appear to be designed off of the optimum performance point.

The Bay Class propeller loading is some 17% lower than Terry Fox, yet the specific net thrust at bollard is higher by a slightly disproportionate 8%, instead of the possible expected figure of 3%. The probable reasons are that the Bay Class have just a single instead of twin propellers, which is also of a lighter design appropriate to its lower ice class.

The different characteristics of controllable pitch relative to fixed pitch propulsion are illustrated in Figure 4.4.2.

At the normal bollard or low speed icebreaking design condition, similar specific net thrusts are attained for both the geared diesel controllable pitch system of Terry Fox and the fixed pitch electric drive systems of the R-Class, Louis S.St.Laurent and Otso. However, as speed increases, specific net thrust for Terry Fox decreases at a significantly slower rate than for the fixed pitch systems. At 8 m/s, Terry Fox's specific net thrust is some 35-40% higher than for vessels with fixed pitch propellers.

Away from the bollard design condition, the fixed pitch systems maintain full power utilisation by increasing shaft speed at the constant fixed pitch, whilst the controllable pitch systems increase pitch, normally at constant shaft revolutions. Clearly, although the combination of fixed pitch propellers and electric drive can match the specific net thrust of the controllable pitch and geared drive system at a specific design condition, the controllable pitch system is better suited to attain overall higher specific net thrust performance.

The proviso is that the fixed pitch system has sufficient additional shaft speed capability and the controllable pitch system sufficient additional pitch capability to maintain constant power.

4.4.3 Conclusions

Propulsive performance, in terms of specific net thrust versus ship speed data, has been determined for the Phase 2 group of vessels, and design comparisons have been made for both open and ducted propulsion systems at the normal full power design condition.

The results confirm the performance levels from Phase 1 which can be attained with open and ducted controllable pitch systems and extend the knowledge base to include fixed pitch systems and the probable effect of the number of propel-

lers,intensity of propeller loading and ice class. Some cases of poor propulsive performance are explained.

The following practical preliminary design information for ducted propulsion systems of icebreakers has been determined.

* The M.V.Arctic data confirm the findings in Phase 1 with regard to the specific net thrust which can be obtained from an intermediate single screw ice class ducted propulsion system which, in association with the hull design, has normal levels of thrust deduction.

* The Oden data provide a level of specific net thrust which can be attained by a twin screw ducted propulsion system designed for unlimited operation in multi-year ice.

Thrust deduction at bollard is normal, whereas that at speed is somewhat high. It is therefore possible that specific net thrust for an unlimited vessel could yet be improved.

* For preliminary design purposes, attainable specific net thrusts for most practical designs should lie between the bounds of the Kigoriak and Oden data.

Similarly, the following practical preliminary design information for open screw propulsion systems of icebreakers has been determined.

* In practical designs, the same specific net thrust can be attained in the design condition for both fixed pitch electric drive and controllable pitch geared drive systems.

* The controllable pitch geared drive system can provide significantly higher specific net thrust performance away from the design condition than the fixed pitch system.

* The Terry Fox curve in Figure 4.4.2 provides a level of specific net thrust which can be attained by a twin screw intermediate ice class vessel with controllable pitch propulsion.

* The curves for the R-Class and Otso provide levels of specific net thrust which can be attained by twin screw intermediate ice class vessels with fixed pitch electric drive propulsion.

* As noted above in the discussion of ducted screw performance, the specific net thrust for higher ice class vessels with heavier scantlings is expected to be lower than that shown in Figure 4.4.2.

The combined Phase 1 and Phase 2 data for specific net thrust and thrust deduction could be used to develop a propulsive performance model for ship powering performance prediction.

4.5 Resistance versus Ice Thickness at Constant Speed

4.5.1 Results

Resistance versus ice thickness data for all trials of all vessels in the Phase 2 group are given in the Appendix Table C4.5 for ship speeds of 1,2 and 3 m/s. As in Phase 1, level ice resistance has been corrected linearly with respect to beam to the common beam of Kigoriak (19.25m). No corrections have been made for environmental and hull conditions.

The data are plotted in Figures 4.5.1 and 4.5.2 for 1 m/s, Figures 4.5.3 and 4.5.4 for 2 m/s and Figures 4.5.5 and 4.5.6 for 3 m/s. For each speed, the data are split into two groups, one with ice flexural strength index of less than, and one greater than 300 kPa.

The data are presented in the following format.

Ship resistance in ice, as in Phase 1, is the total resistance due to icebreaking, submergence and clearing of ice, including hydrodynamic resistance.

Ship speeds are given in metres per second (m/s) at the same three speeds of 1,2 and 3 m/s used in Phase 1.

Ice and snow cover thickness are given, in metres, as an equivalent ice thickness, as in Phase 1, of ice thickness plus one half snow thickness.

For the purposes of investigating the effect of basic ship design features and parameters upon icegoing resistance, performance data with hull lubrication systems operating are excluded. The effect of these systems is dealt with separately in Section 4.6.

A considerable degree of confidence in the resistance data presented has been obtained in the analysis process through the following means.

* Exclusion of all data where the ice conditions were not essentially level and homogeneous and where the ice was under pressure.

* Working from original trials data, plus model test propulsion data where considered appropriate and available, to obtain both resistance and propulsive performance. The logical trends obtained in much of the propulsive performance data provide support for the validity of the associated resistance data.

The resistance data in Figures 4.5.1 to 6, include the effect of ship design parameters and features as well as of environmental and hull conditions. Consequently, as in the case of speed versus level ice thickness and power versus ice thick-

ness in Sections 4.2 and 4.3 above, they can only be used for comparative purposes in a very limited and cautious manner.

The same logical trends noted for power versus level ice thickness are still evident. Resistance of Radisson and Franklin in similar high strength ice are virtually identical. The contemporary vessel Mudyug-New has a lower thickness exponent than conventional vessels in the group and the resistance of the Polar Class lies logically between that of M.V.Arctic-Old and New.

However, in order to analyse the data to the required higher level of understanding, a concurrent analysis of all significant environmental and ship parameters must be conducted. This analysis is carried out and reported in Chapter 11.

4.5.2 Conclusions

Resistance versus level ice thickness data at constant speeds have been presented for all trials of all vessels in the Phase 2 group. The analysis process has provided a considerable degree of confidence in the accuracy of the data. However, the data apply only for the specific environmental and hull conditions at the time of the individual trials. Therefore, the data as presented can only be used to compare the resistance of different vessels in a limited and cautious manner. Some logical trends are nevertheless noted.

In order to determine the effect of hull form parameters and features upon level ice resistance, further analysis of the data, including concurrent analysis of the effect of environmental and hull conditions, was carried out as reported in chapter 11.

4.6 Influence of Hull Lubrication Systems

4.6.1 General

Information is available for five of the Phase 2 group of vessels on the effect of hull lubrication systems upon level ice power requirements. Four different forms of hull lubrication system are represented.

- Wartsila air bubbler system on M.V.Arctic-Old, Katmai Bay and Otso. High pressure air is ejected from the bilge region along the side of the vessel. Otso has a very high powered system (1.9 MW) with air ejected also around the bow.

- Air/water jets on Mudyug-New. High pressure water jets with passive air induction are ejected along the bow/ice interface.

- Water curtain on Mudyug-New. Water jets directed verti-

cally down onto the ice in front of the bow/ice interface form a curtain across the width of the bow.

- Bow wash system on Oden. Low pressure gravity dump of large volume of water immediately in front of bow/ice interface.

The hull lubrication systems influence level ice powering through friction reduction, due primarily to lubrication of contact between ice and the hull and also in the case of high pressure water jets, lowered pressure of ice on the hull.

Among the Phase 2 group of vessels, the Henry Larsen in also fitted with a Wartsila air bubbler system. However, no trials data are available.

All available data on the above hull lubrication systems are analysed and presented below. Their performance is compared with that presented in the Phase 1 project.

4.5.2 Data Analysis

Full scale level ice performance tests have been carried out on the above vessels both with and without the hull lubrication systems operating. For each vessel and hull lubrication system, the tests both "with" and "without" were carried out in the same ice conditions. Comparisons may therefore be made directly from the data without the need of corrections for ice properties.

The data are analysed and presented in terms of the system efficiency ratio.

* Shaft power reduction due to operation of the system divided by power required to operate the system.

Consequently, when this ratio is greater than 1, there is a net power saving in operating the system and vice-versa.

The data available are obtained for M.V.Arctic-Old, Katmai Bay and Oden from the level ice performance analysis in Appendic C, and for Otso and Mudyug-New, directly from the reference reports. Differences in the power required for the vessel to traverse level ice at a specific speed due to operation of the hull lubrication system are calculated and then divided by the system power. All data are listed in Appendix Table C 4.6.1, which gives system efficiency ratio versus level ice thickness for different ship speeds in the prevailing ice conditions. The data are plotted in Figure 4.6.1 together with the data from Phase 1.

4.6.3 Results

The results for the system efficiency of the bubbler systems on M.V.Arctic, Katmai Bay and Otso, show that in level ice

without pressure, the air bubbler rarely saves as much shaft power as the system consumes. The best results, although barely greater than 1.0 for system efficiency, are obtained by Katmai Bay in the higher friction conditions of cold Winter ice. These results confirm the finding in Phase 1 in relation to the performance of Terry Fox's bubbler system. The low system efficiency of the bubbler system in transit of level non-pressured ice is due to the fact that the lubrication is not provided where it would be most effective. This is clearly the case for M.V.Arctic and Katmai Bay, where hull lubrication is provided only along the sides of the vessel. On the Otso, air bubbling action at the bow has clearly not resulted in significant lubrication at the ice and hull interface.

The water curtain system on Mudyug-New does not provide overall power savings. This may appear unusual in view of the high system efficiency determined for the somewhat similar low pressure water lube system of Kigoriak in Phase 1. However, it may be explained by two important differences in design. The water flow on the Mudyug water curtain system of 4000 m^3/hr is only one third of that on the Kigoriak system. It is also applied on the ice somewhat further forward of the icebreaking zone. This indicates that the placement and volume of water lubrication may be critical to the effectiveness of the bow wash system.

The air/water jet system on Mudyug-New provides overall power savings of up to twice system power. The power savings increase with forward speed. However, the system efficiency is considerably lower than that of the low pressure water lube system on Kigoriak. The Mudyug trials were however carried out in the Baltic, which does not experience such cold, high friction conditions as were present for the Kigoriak Beaufort sea trials. It is expected that the air/water jet system would be more effective than as indicated in Figure 4.6.1 in Beaufort sea Winter conditions.

The low pressure bow wash system on Oden has a system efficiency of up to 2.0 at 4 m/s. The system provides 18000 m^3/hr of water on the ice, which is the same volume per unit bow width as for the fairly similar system on Kigoriak. However, system efficiency is lower than reported for Kigoriak. As in the case of Mudyug, however, the Oden trials were carried out in relatively low friction conditions, where fewer gains can be made through reducing friction. It is therefore expected that the Oden bow wash system would be more effective than as indicated in Figure 4.6.1 in Beaufort sea Winter conditions.

Comparing the Mudyug-Old air/water jet system with Oden 2's low pressure water lube system, it is noted that as in Phase 1, the efficiency of effective systems improves with both ice thickness and ship speed.

4.6.4 Conclusions

The Phase 2 information on the effect of hull lubrication on non-pressured level ice powering performance both confirms and supplements the findings from the Phase 1 study. The combined findings are.

* For hull lubrication systems to be effective, the lubrication must be provided where it is most effective, at the bow hull and ice interface.

* The efficiency of effective systems increases with increase in ship speed and ice thickness.

* System efficiency is lower in warm low friction ice conditions than in cold high friction ice conditions.

* Most air bubbler systems provide lubrication predominantly along the sides of a vessel and therefore do not normally provide overall powering advantages. Where it has been attempted to extend coverage to the bow region, this does not appear to have provided significant lubrication at the bow and ice interface.

* Systems such as Kigoriak's and Oden's bow wash and Mudyug's air/water jets, provide lubrication at the bow and ice interface and subsequently provide overall power savings.

* The Mudyug water curtain system is non-effective, possibly because it does not provide sufficient water at the correct location.

* Due to the generally lower friction conditions of the ice in the Phase 2 data, system efficiencies as high as those shown for the Kigoriak in Phase 1 might not be expected. Whether or not the effectiveness of the Oden's bow wash and Mudyug's air/water jets will reach that of the Kigoriak bow lube system, in similar very high friction conditions, remains to be determined.

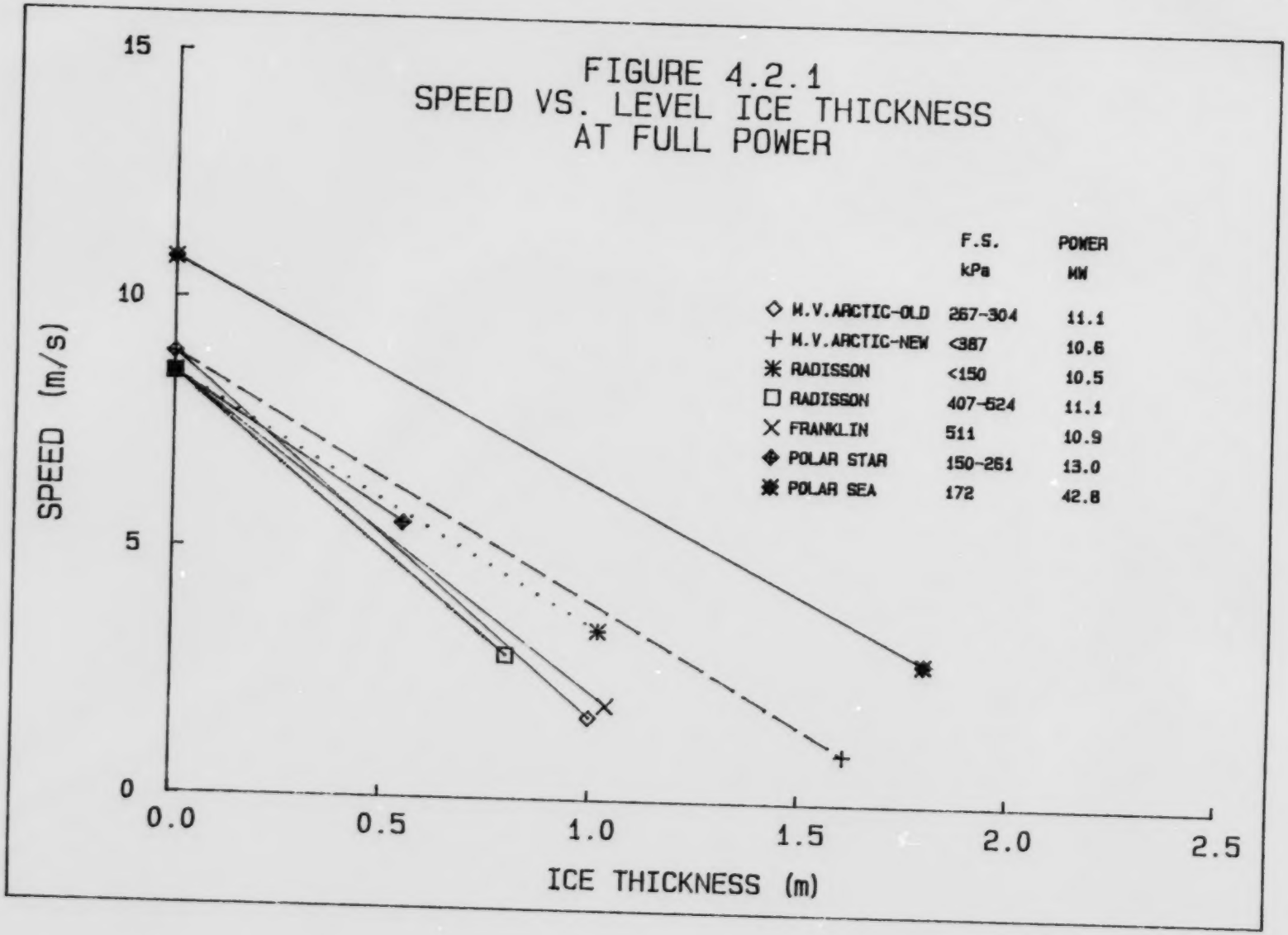


FIGURE 4.2.1
SPEED VS. LEVEL ICE THICKNESS
AT FULL POWER
F.S. kPa
POWER MW
M.V.ARCTIC-OLD 267-304 11.1
M.V.ARCTIC-NEW <387 10.6
RADISSON <150 10.5
RADISSON 407-524 11.1
FRANKLIN 511 10.9
POLAR STAR 150-261 13.0
POLAR SEA 172 42.8
SPEED (m/s)
15
10
5
0
0.0
0.5
1.0
1.5
2.0
2.5
ICE THICKNESS (m)

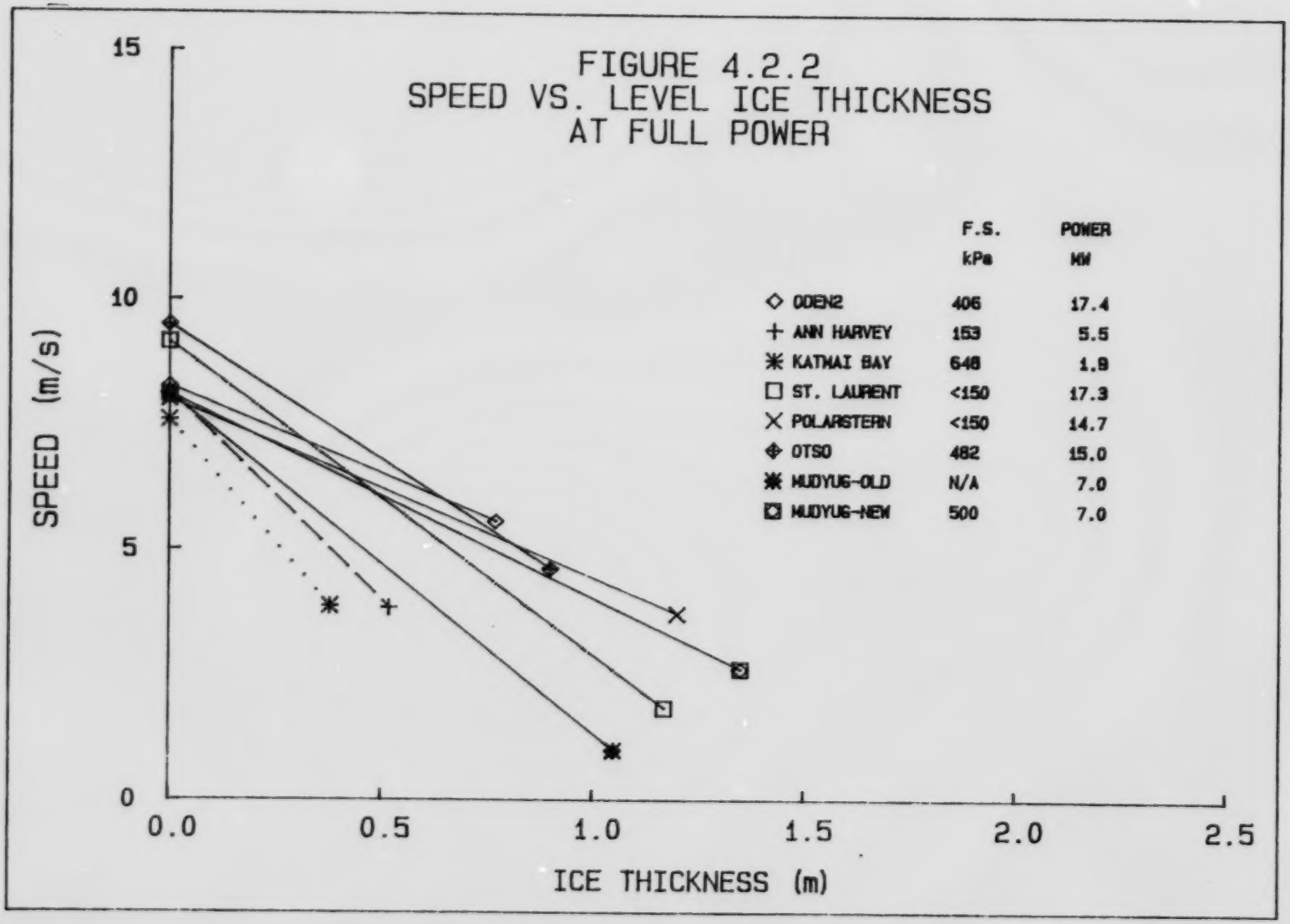


FIGURE 4.2.2
SPEED VS. LEVEL ICE THICKNESS
AT FULL POWER
F.S. kPa
POWER MW
ODEN2 406 17.4
ANN HARVEY 153 5.5
KATMAI BAY 648 1.9
ST. LAURENT <150 17.3
POLARSTERN <150 14.7
OTSO 482 15.0
MUDYUG-OLD N/A 7.0
MUDYUG-NEW 500 7.0
SPEED (m/s)
15
10
5
0
0.0
0.5
1.0
1.5
2.0
2.5
ICE THICKNESS (m)

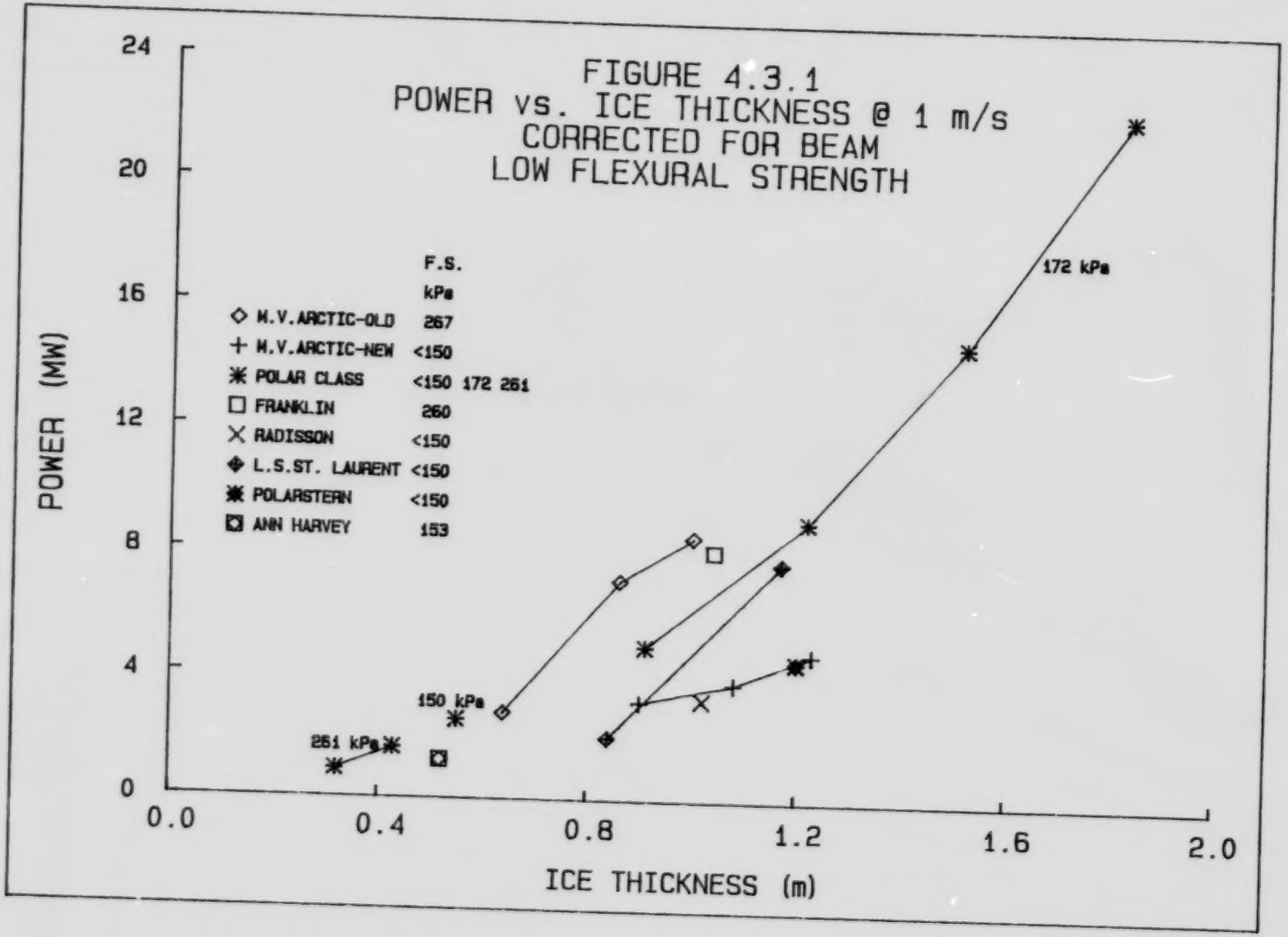


FIGURE 4.3.1
POWER vs. ICE THICKNESS @ 1 m/s
CORRECTED FOR BEAM
LOW FLEXURAL STRENGTH
POWER (MW)
ICE THICKNESS (m)
0
4
8
12
16
20
24
0.0
0.4
0.8
1.2
1.6
2.0
F.S.
kPa
M.V.ARCTIC-OLD 267
M.V.ARCTIC-NEW <150
POLAR CLASS <150 172 251
FRANKLIN 260
RADISSON <150
L.S.ST. LAURENT <150
POLARSTERN <150
ANN HARVEY 153
172 kPa
150 kPa
251 kPa

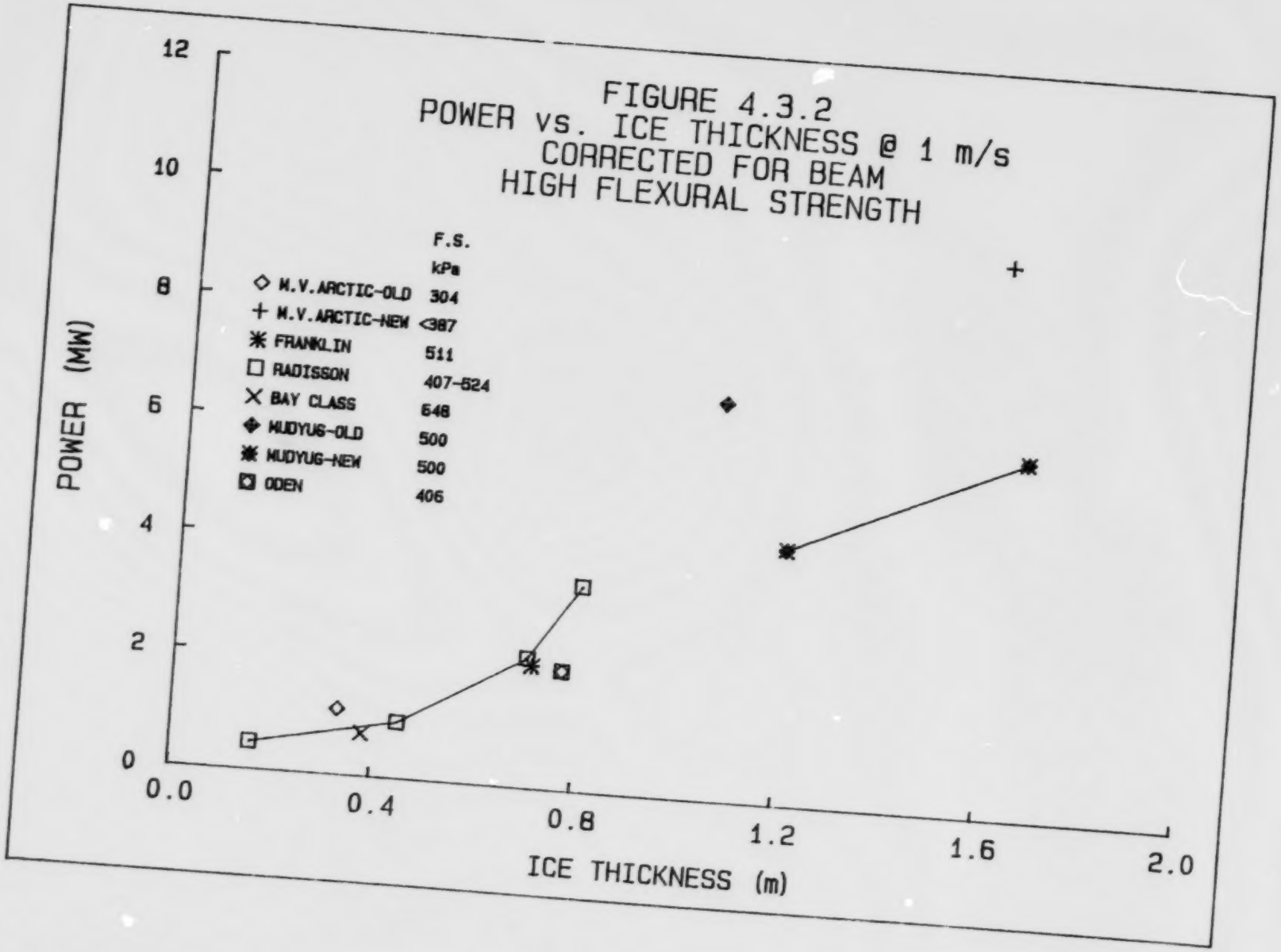


FIGURE 4.3.2
POWER vs. ICE THICKNESS @ 1 m/s
CORRECTED FOR BEAM
HIGH FLEXURAL STRENGTH
F.S.
kPa
M.V.ARCTIC-OLD 304
M.V.ARCTIC-NEW <387
FRANKLIN 511
RADISSON 407-524
BAY CLASS 648
MUDYUG-OLD 500
MUDYUG-NEW 500
ODEN 406
POWER (MW)
ICE THICKNESS (m)
0
2
4
6
8
10
12
0.0
0.4
0.8
1.2
1.6
2.0

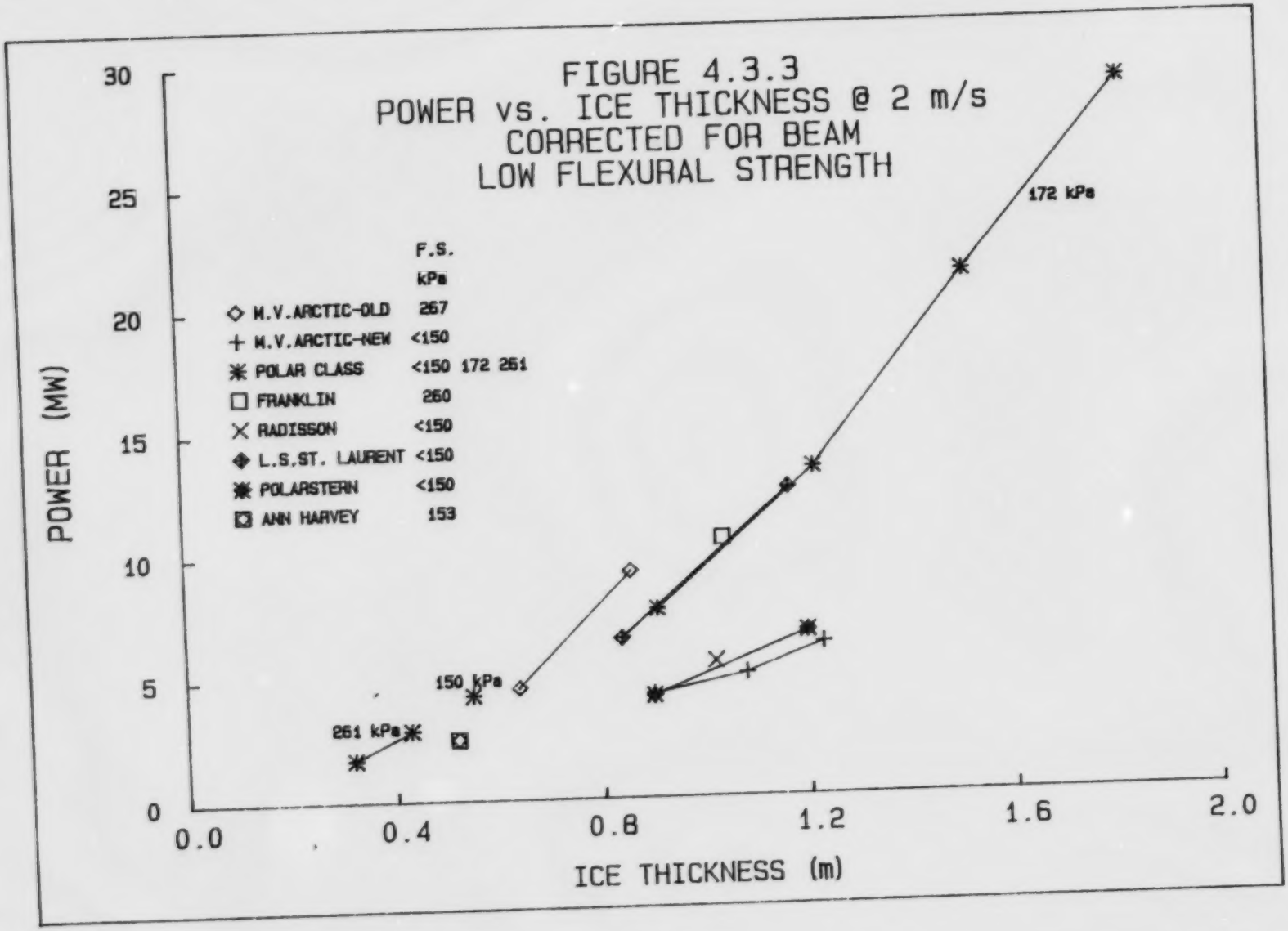


FIGURE 4.3.3
POWER vs. ICE THICKNESS @ 2 m/s
CORRECTED FOR BEAM
LOW FLEXURAL STRENGTH
POWER (MW)
ICE THICKNESS (m)
0
5
10
15
20
25
30
0.0
0.4
0.8
1.2
1.6
2.0
F.S.
kPa
M.V.ARCTIC-OLD 267
M.V.ARCTIC-NEW <150
POLAR CLASS <150 172 251
FRANKLIN 260
RADISSON <150
L.S.ST. LAURENT <150
POLARSTERN <150
ANN HARVEY 153
172 kPa
150 kPa
251 kPa

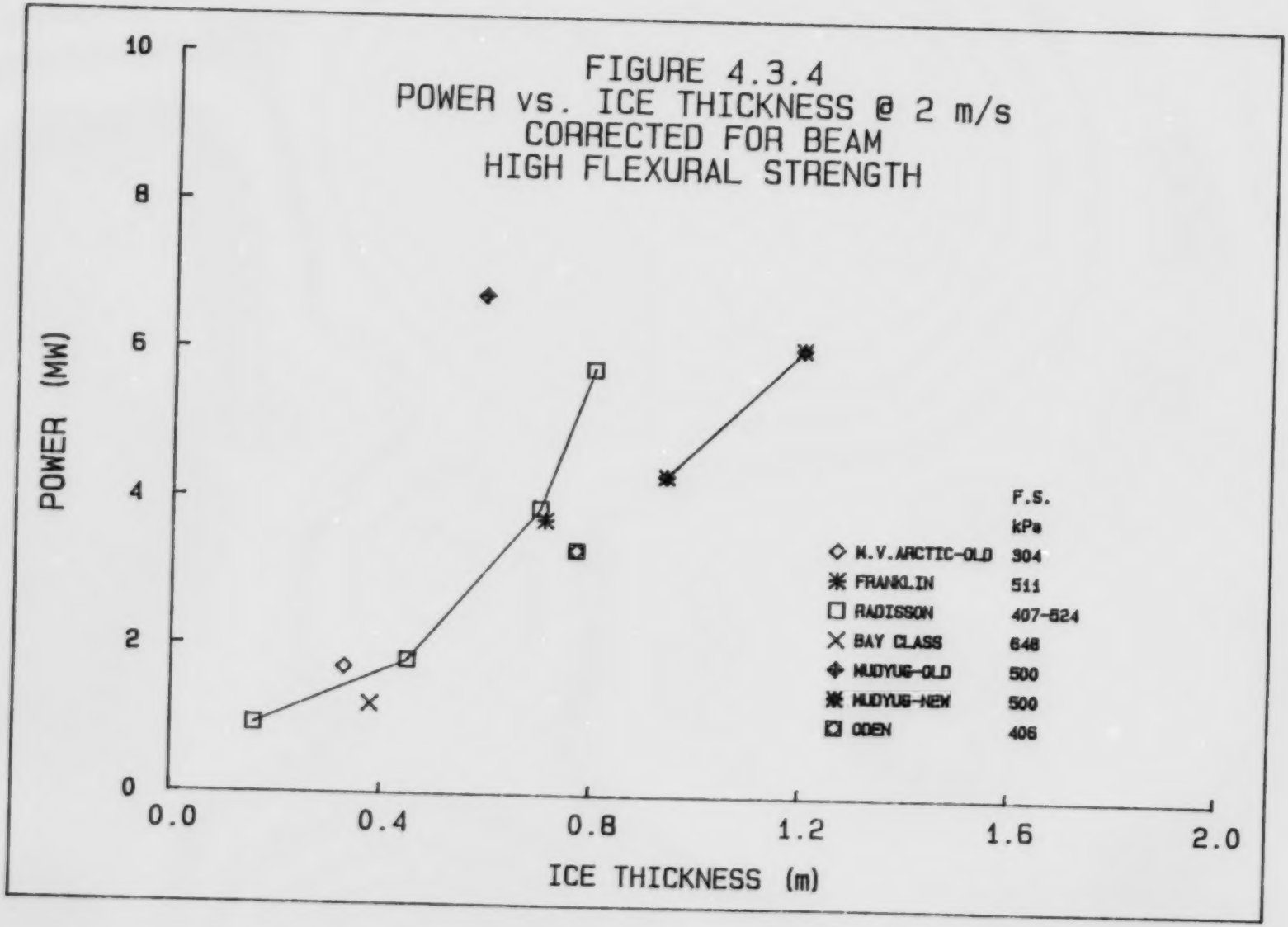


FIGURE 4.3.4
POWER vs. ICE THICKNESS @ 2 m/s
CORRECTED FOR BEAM
HIGH FLEXURAL STRENGTH
POWER (MW)
ICE THICKNESS (m)
0
2
4
6
8
10
0.0
0.4
0.8
1.2
1.6
2.0
F.S.
kPa
M.V.ARCTIC-OLD 304
FRANKLIN 511
RADISSON 407-624
BAY CLASS 648
MUDYUG-OLD 500
MUDYUG-NEW 500
ODEN 406

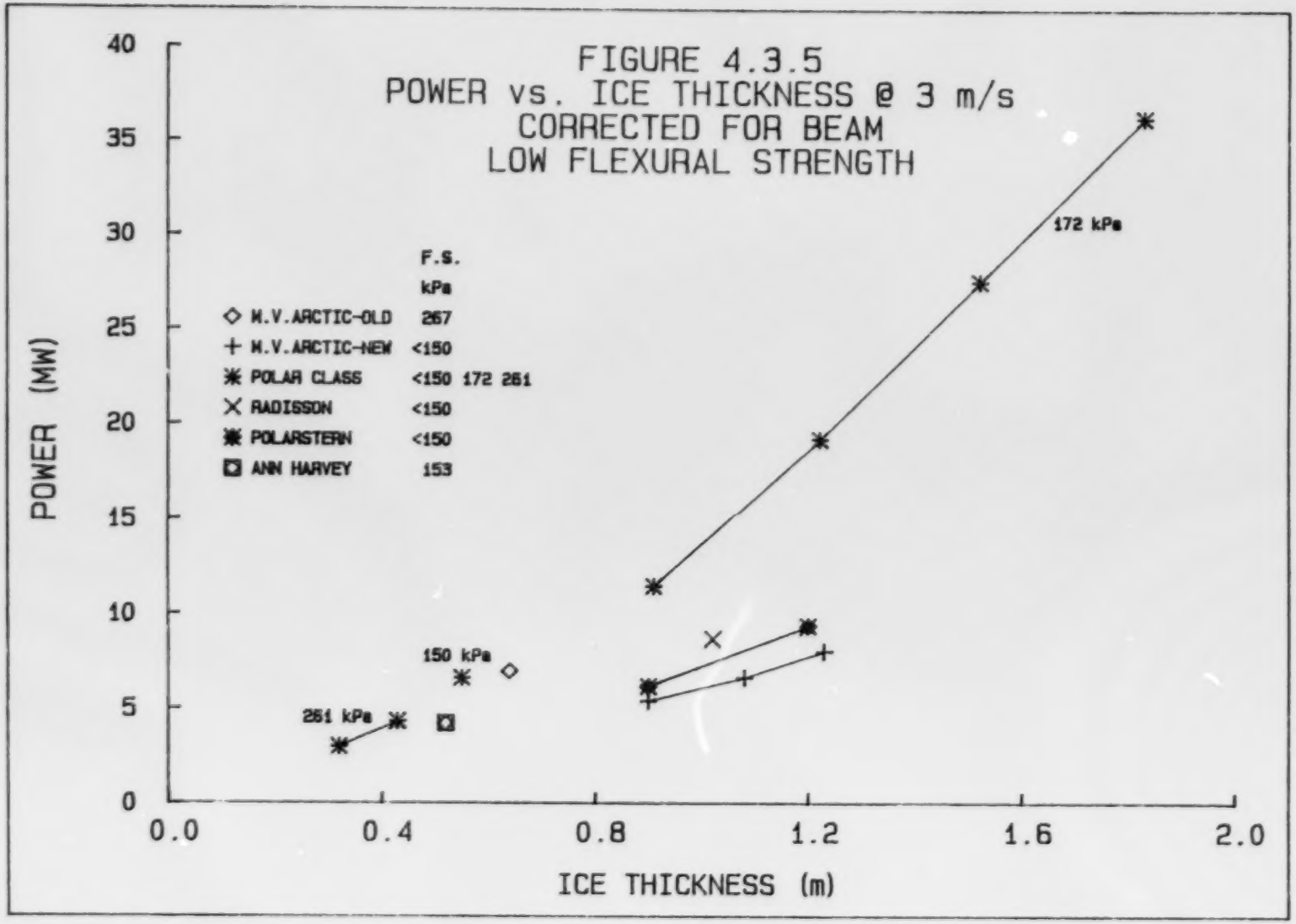


FIGURE 4.3.5
POWER vs. ICE THICKNESS @ 3 m/s
CORRECTED FOR BEAM
LOW FLEXURAL STRENGTH
POWER (MW)
ICE THICKNESS (m)
0
5
10
15
20
25
30
35
40
0.0
0.4
0.8
1.2
1.6
2.0
F.S.
kPa
M.V.ARCTIC-OLD 267
M.V.ARCTIC-NEW <150
POLAR CLASS <150 172 261
RADISSON <150
POLARSTERN <150
ANN HARVEY 153
172 kPa
150 kPa
261 kPa

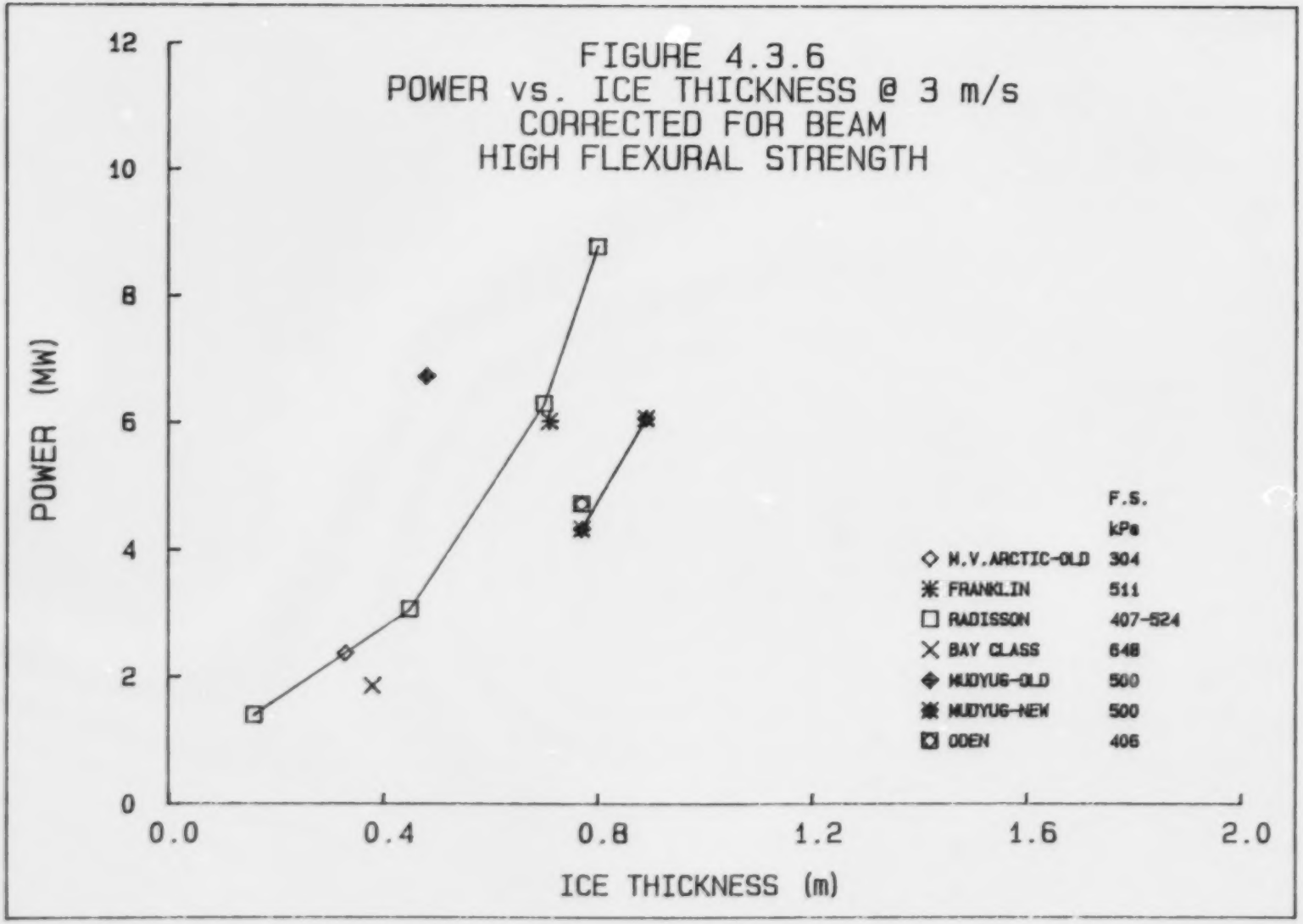
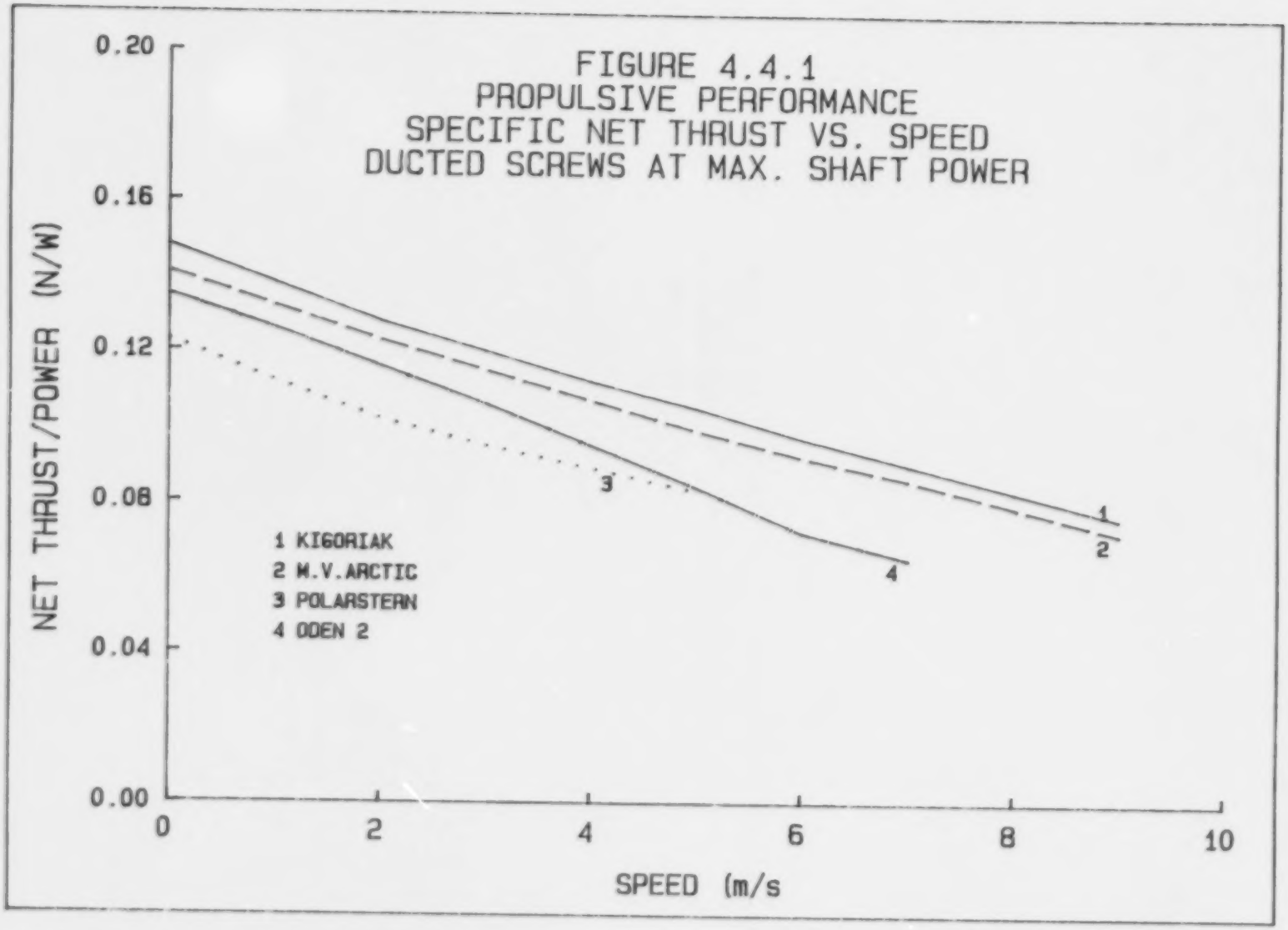


FIGURE 4.3.6
POWER vs. ICE THICKNESS @ 3 m/s
CORRECTED FOR BEAM
HIGH FLEXURAL STRENGTH
POWER (MW)
ICE THICKNESS (m)
0
2
4
6
8
10
12
0.0
0.4
0.8
1.2
1.6
2.0
F.S.
kPa
M.V.ARCTIC-OLD 304
FRANKLIN 511
RADISSON 407-524
BAY CLASS 648
MUDYUG-OLD 500
MUDYUG-NEW 500
ODEN 406

FIGURE 4.4.1
PROPULSIVE PERFORMANCE
SPECIFIC NET THRUST VS. SPEED
DUCTED SCREWS AT MAX. SHAFT POWER



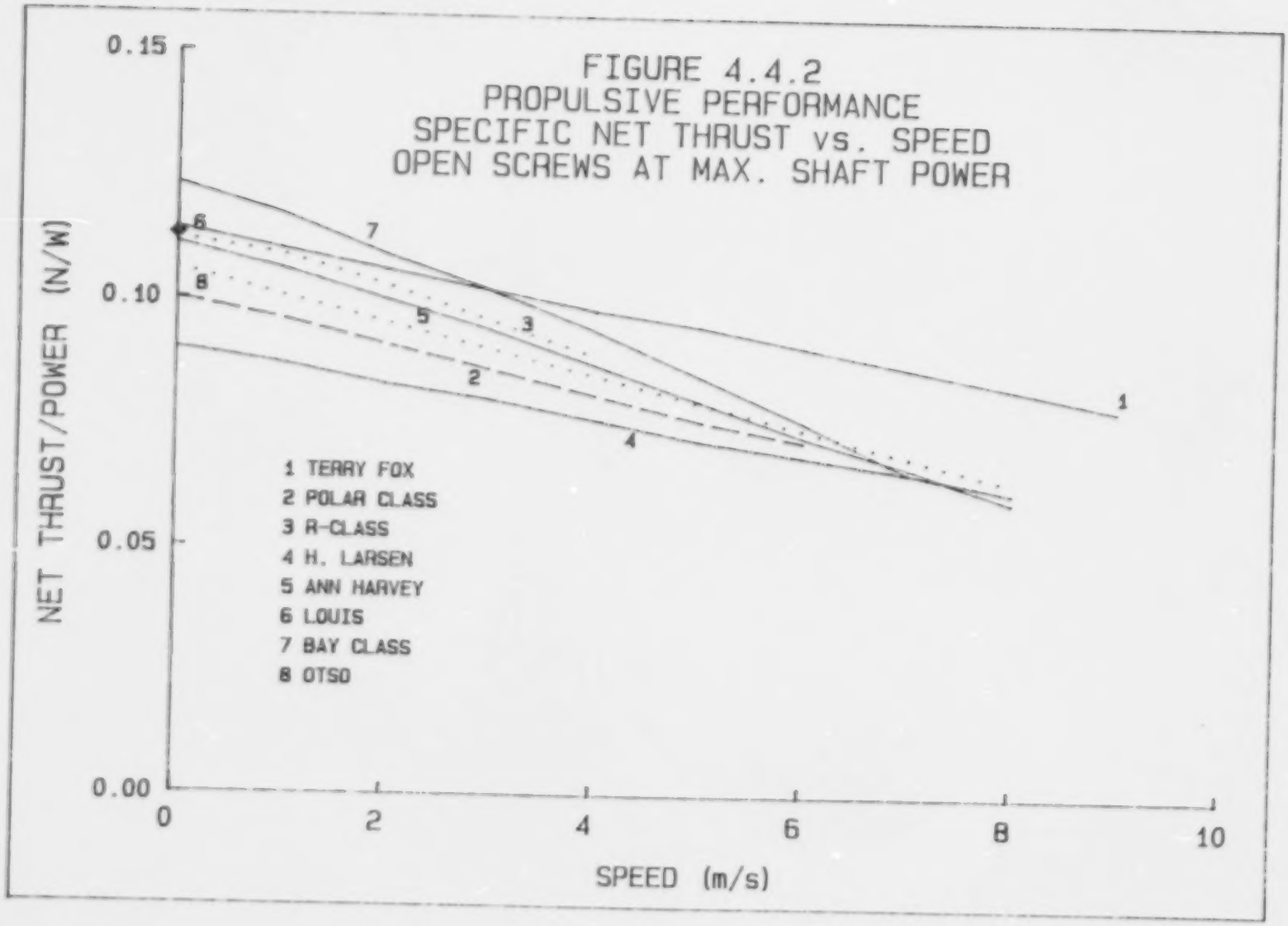


FIGURE 4.4.2
PROPULSIVE PERFORMANCE
SPECIFIC NET THRUST vs. SPEED
OPEN SCREWS AT MAX. SHAFT POWER
NET THRUST/POWER (N/W)
0.15
0.10
0.05
0.00
0
2
4
6
8
10
SPEED (m/s)
1 TERRY FOX
2 POLAR CLASS
3 R-CLASS
4 H. LARSEN
5 ANN HARVEY
6 LOUIS
7 BAY CLASS
8 OTSO

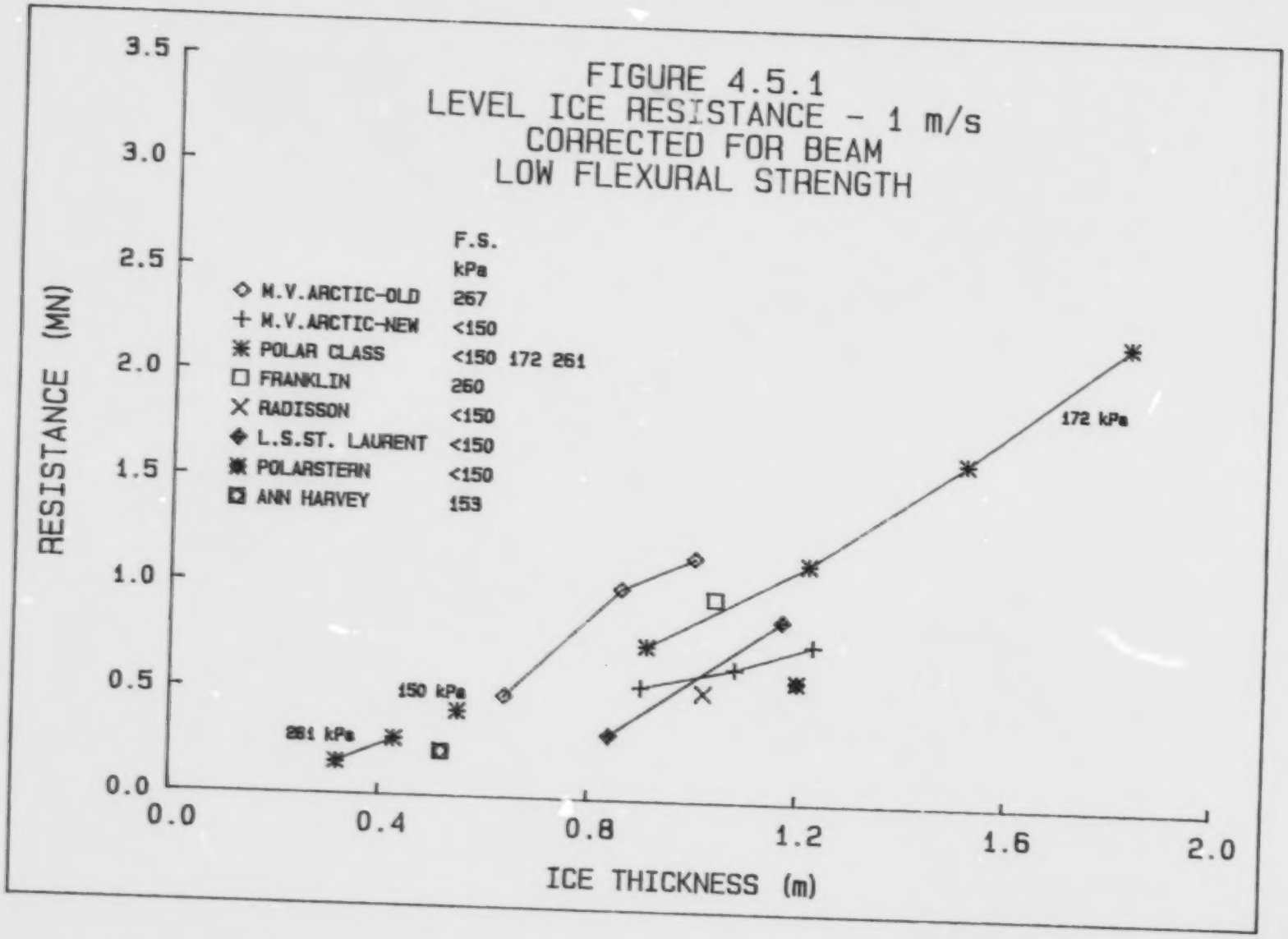


FIGURE 4.5.1
LEVEL ICE RESISTANCE - 1 m/s
CORRECTED FOR BEAM
LOW FLEXURAL STRENGTH
F.S.
kPa
M.V.ARCTIC-OLD 267
M.V.ARCTIC-NEW <150
POLAR CLASS <150 172 261
FRANKLIN 260
RADISSON <150
L.S.ST. LAURENT <150
POLARSTERN <150
ANN HARVEY 153
172 kPa
150 kPa
261 kPa
RESISTANCE (MN)
ICE THICKNESS (m)
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
0.0
0.4
0.8
1.2
1.6
2.0

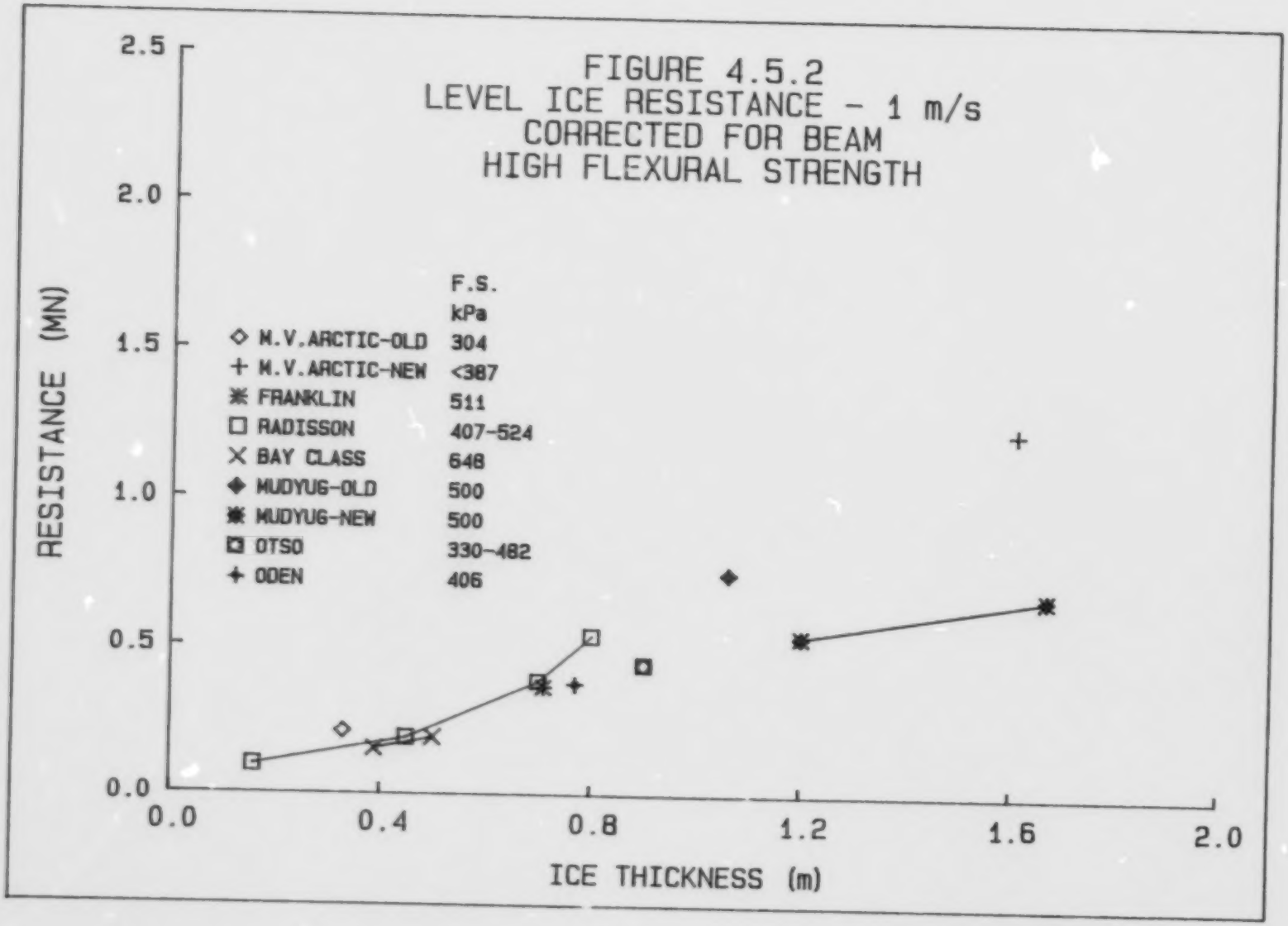


FIGURE 4.5.2
LEVEL ICE RESISTANCE - 1 m/s
CORRECTED FOR BEAM
HIGH FLEXURAL STRENGTH
RESISTANCE (MN)
ICE THICKNESS (m)
2.5
2.0
1.5
1.0
0.5
0.0
0.0
0.4
0.8
1.2
1.6
2.0
F.S.
kPa
M.V.ARCTIC-OLD 304
M.V.ARCTIC-NEW <387
FRANKLIN 511
RADISSON 407-524
BAY CLASS 648
MUDYUG-OLD 500
MUDYUG-NEW 500
OTSO 330-482
ODEN 406

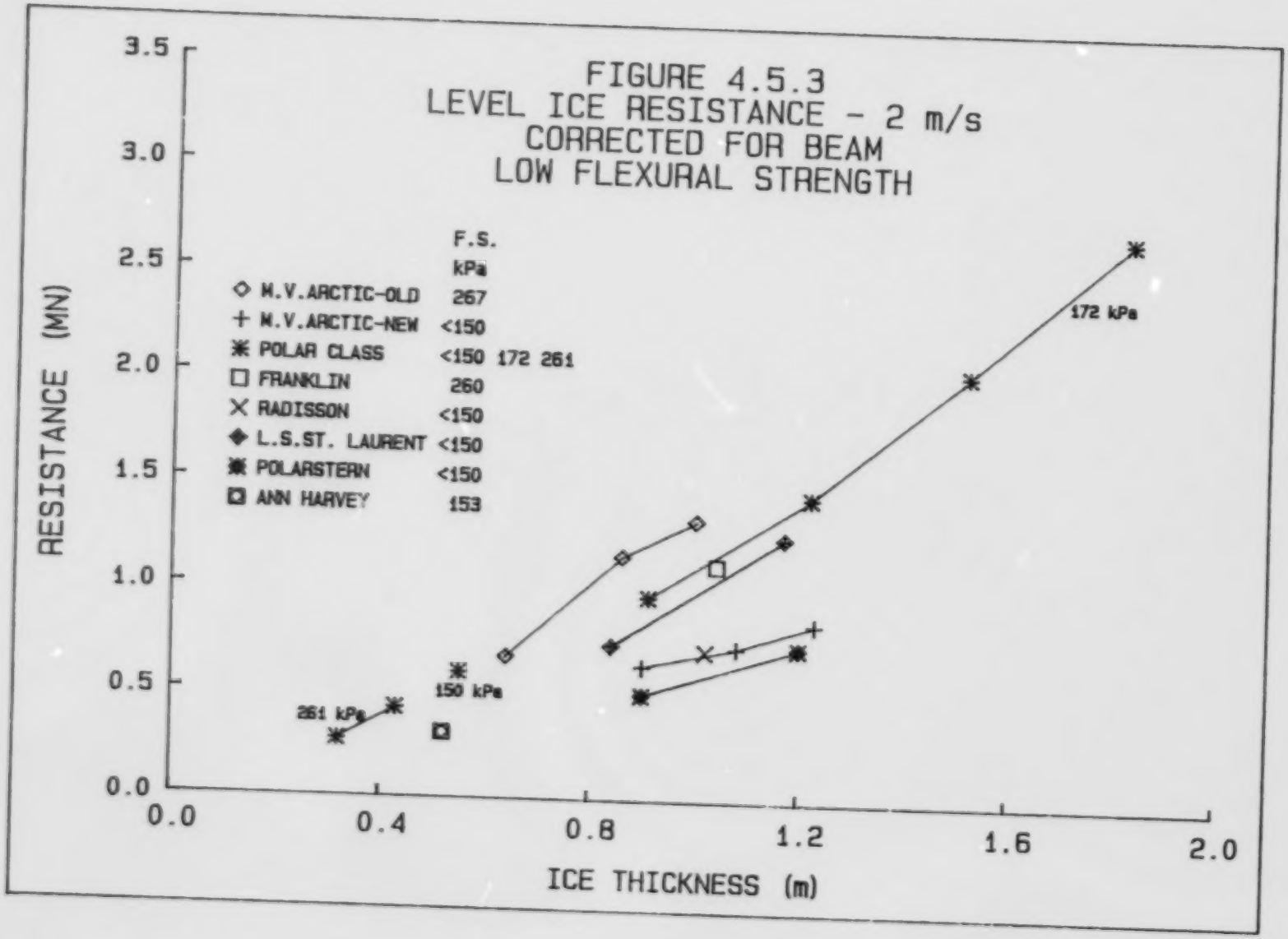


FIGURE 4.5.3
LEVEL ICE RESISTANCE - 2 m/s
CORRECTED FOR BEAM
LOW FLEXURAL STRENGTH
F.S.
kPa
M.V.ARCTIC-OLD 267
M.V.ARCTIC-NEW <150
POLAR CLASS <150 172 261
FRANKLIN 260
RADISSON <150
L.S.ST. LAURENT <150
POLARSTERN <150
ANN HARVEY 153
172 kPa
150 kPa
261 kPa
RESISTANCE (MN)
ICE THICKNESS (m)
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
0.0
0.4
0.8
1.2
1.6
2.0

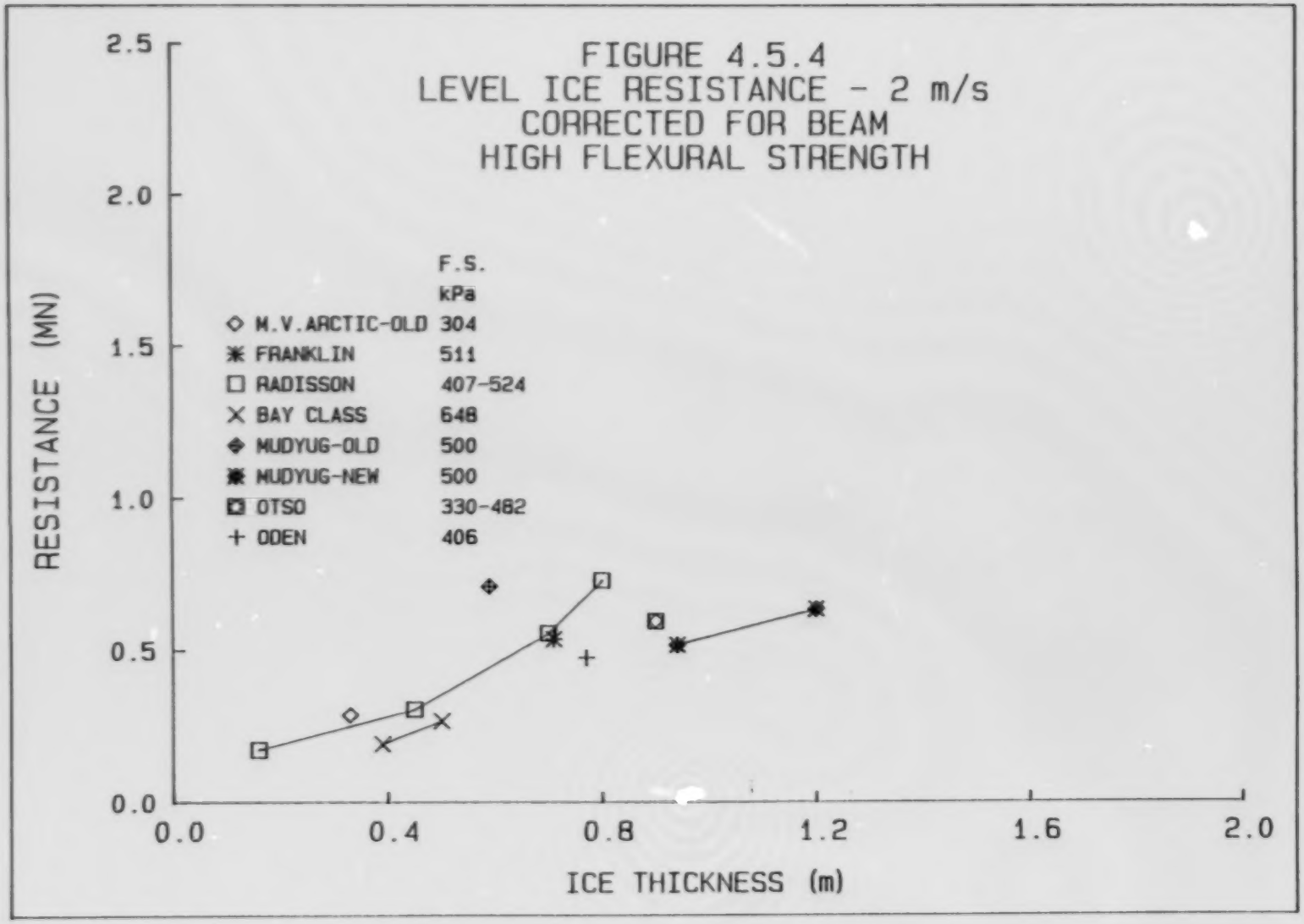


FIGURE 4.5.4
LEVEL ICE RESISTANCE - 2 m/s
CORRECTED FOR BEAM
HIGH FLEXURAL STRENGTH
F.S.
kPa
M.V.ARCTIC-OLD 304
FRANKLIN 511
RADISSON 407-524
BAY CLASS 648
MUDYUG-OLD 500
MUDYUG-NEW 500
OTSO 330-482
ODEN 406
RESISTANCE (MN)
2.5
2.0
1.5
1.0
0.5
0.0
0.0
0.4
0.8
1.2
1.6
2.0
ICE THICKNESS (m)

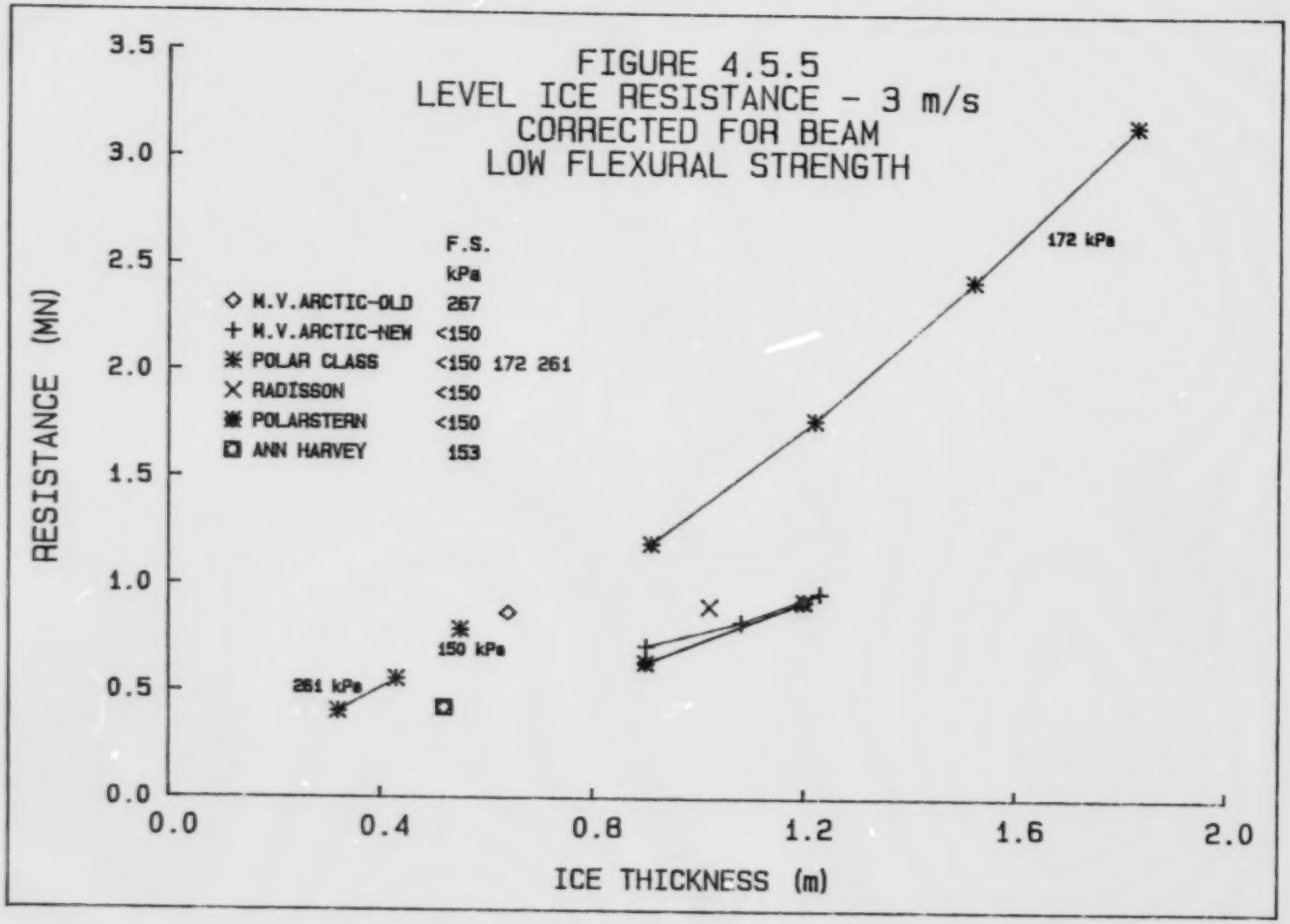


FIGURE 4.5.5
LEVEL ICE RESISTANCE - 3 m/s
CORRECTED FOR BEAM
LOW FLEXURAL STRENGTH
F.S.
kPa
M.V.ARCTIC-OLD 267
M.V.ARCTIC-NEW <150
POLAR CLASS <150 172 261
RADISSON <150
POLARSTERN <150
ANN HARVEY 153
172 kPa
150 kPa
261 kPa
RESISTANCE (MN)
ICE THICKNESS (m)
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
0.0
0.4
0.8
1.2
1.6
2.0

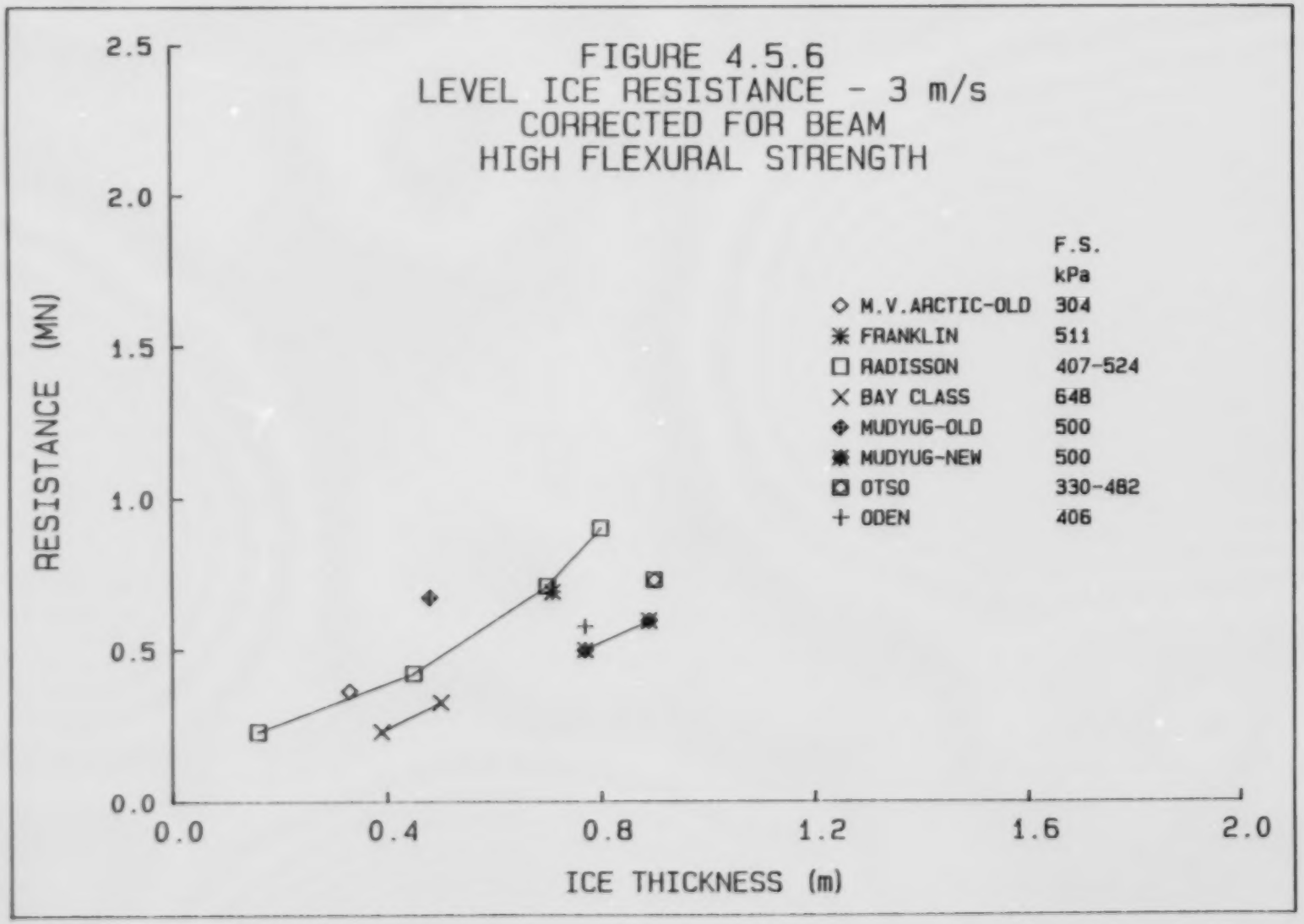


FIGURE 4.5.6
LEVEL ICE RESISTANCE - 3 m/s
CORRECTED FOR BEAM
HIGH FLEXURAL STRENGTH
RESISTANCE (MN)
ICE THICKNESS (m)
2.5
2.0
1.5
1.0
0.5
0.0
0.0
0.4
0.8
1.2
1.6
2.0
F.S.
kPa
M.V.ARCTIC-OLD 304
FRANKLIN 511
RADISSON 407-524
BAY CLASS 648
MUDYUG-OLD 500
MUDYUG-NEW 500
OTSO 330-482
ODEN 406

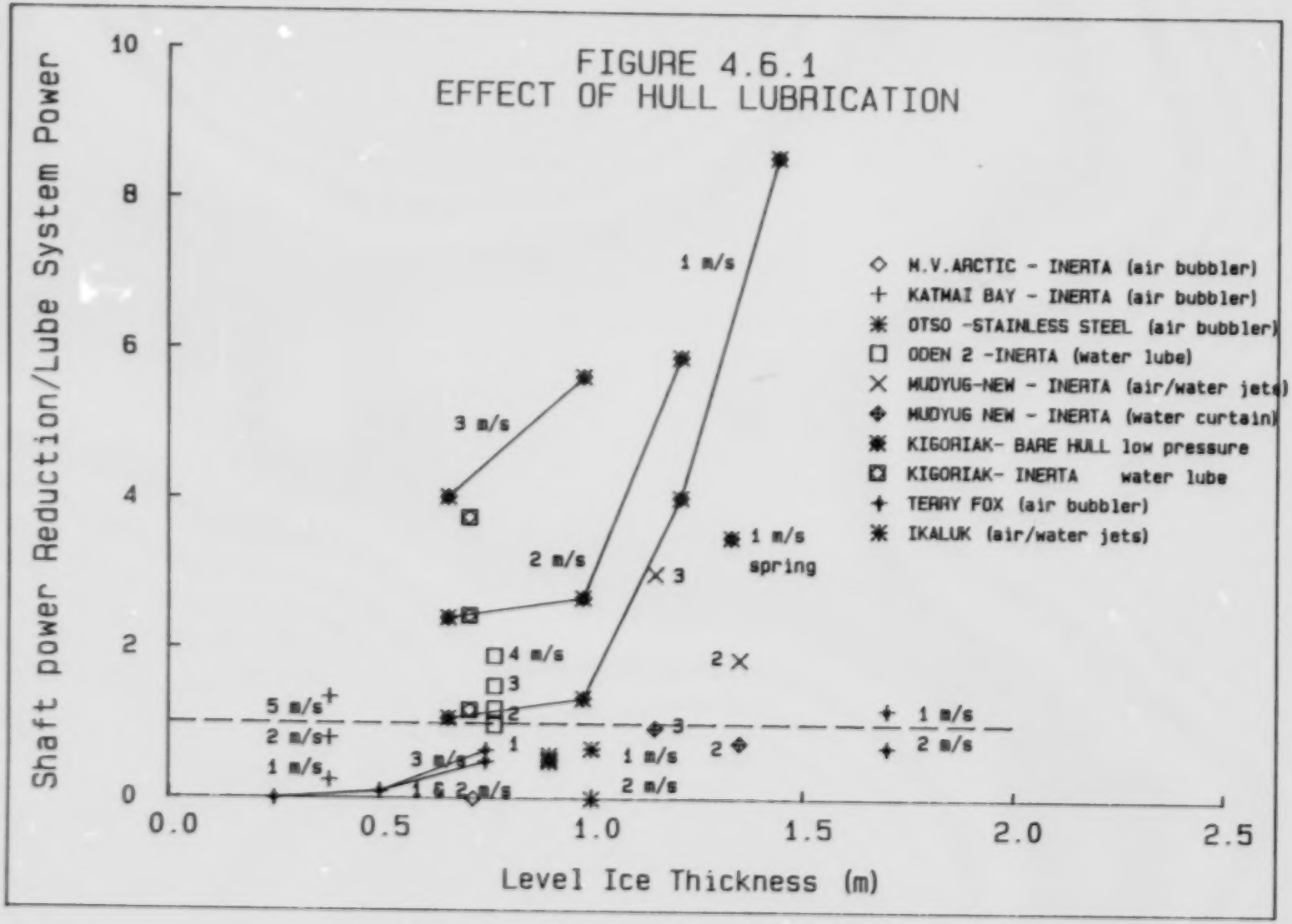


FIGURE 4.6.1
EFFECT OF HULL LUBRICATION
Shaft power Reduction/Lube System Power
Level Ice Thickness (m)
0
2
4
6
8
10
0.0
0.5
1.0
1.5
2.0
2.5
M.V.ARCTIC - INERTA (air bubbler)
KATMAI BAY - INERTA (air bubbler)
OTSO -STAINLESS STEEL (air bubbler)
ODEN 2 -INERTA (water lube)
MUDYUG-NEW - INERTA (air/water jets)
MUDYUG NEW - INERTA (water curtain)
KIGORIAK- BARE HULL low pressure
KIGORIAK- INERTA water lube
TERRY FOX (air bubbler)
IKALUK (air/water jets)
1 m/s
3 m/s
2 m/s
1 m/s
spring
4 m/s
5 m/s
2 m/s
1 m/s
3 m/s
1 & 2 m/s
1 m/s
2 m/s
1 m/s
2 m/s

5.0 CHANNEL PERFORMANCE

5.1 General

In Phase 1 there were only limited data available for the performance of the vessels in channels, and where they were available, the properties of the channels were not known other than that they were all newly broken channels. Data covered performance both ahead and astern.

Data are available for eight vessels in the Phase 2 group, but whereas the documentation is more complete, only ahead performance, again in newly broken channels, is covered.

The means of comparison between the vessels is selected as the same as in Phase 1. Namely, the resistance in the channel at a particular speed divided by the resistance in breaking the same level ice at the same speed.

5.2 Analysis

Analysis of the resistance of the vessels M.V.Arctic-New, Franklin, Louis S St Laurent, Polarstern, Katmai Bay, Anne Harvey, Otso and Oden, in newly broken channels, is given in Appendix Tables C 5.2.2 to 5.2.12 respectively. The resistance curves are plotted in Appendix Figures C 5.2.2 to 5.2.12 respectively, together with the appropriate level ice resistance curves. In most cases, the channel curves cover a higher speed range than the level ice curves but with some measure of overlap. In these areas of overlap, the ratios of channel resistance divided by level ice resistance have been calculated.

The analysed data are given in Appendix Table C 5.2.13, together with additional information on channel coverage and ice strength. The values for channel resistance divided by level ice resistance are plotted against ice thickness in Figure 5.1, together with the equivalent data from Phase 1.

5.3 Results

It is noted in Figure 5.1 that the Phase 2 data cover a wider speed range than those of Phase 1 and that most Phase 2 data points are lower than those of Phase 1.

Phase 2 data are only available at one ice thickness per vessel, such that the effect of ice thickness variation cannot be determined. In Phase 1, the Kigoriak data showed decreasing channel resistance coefficient with increase in ice thickness.

The effect of forward speed is noted as being negligible for Otso and Oden, but gives rise to some increase in the channel resistance coefficient for Katmai Bay, Ann Harvey and Fran-

klin. In Phase 1, increase in forward speed resulted in a decrease in channel resistance coefficient for Kigoriak and increase for Kalvik.

It is not possible to determine definitive conclusions from the assembled data, but some overall observations can be made.

Consider the relative values of the channel resistance coefficient for the Phase 2 vessels at forward speeds in the range of 3-5 m/s. It is noted that the coefficient increases, relative to the general characteristics of the Phase 1 data, in the order of vessels :

- Louis S.St.Laurent
- Ann Harvey
- Katmai Bay
- Franklin
- Otso
- Oden
- Polarstern
- M.V.Arctic

The Louis S.St.Laurent and Oden are recorded as being in less than full channel coverage and are therefore not considered further.

The bow angles and relative order of increasing open water resistance per unit displacement, from Chapter 7, Open Water Performance, are:

Vessel	Average buttock angle	Average flare angle	O.W.Res/Displt order
Ann Harvey	29.9	40.2	1 Lowest
Katmai Bay	24.4	38.0	2
Franklin	28.3	40.5	4
Otso	21.1	42.8	Not given
Polarstern	23.0	45.0	5 Highest
M.V.Arctic	20.5	54.8	3

Where the list is in the order of increasing channel resistance coefficient.

On the basis that level icebreaking resistance will generally decrease with decrease in buttock angle and increase in flare angle, it is observed that there is an overall trend for the most efficient icebreaking forms, which are also generally the least efficient open water forms, to have the higher channel resistance coefficient. The Phase 1 data as a whole, which have generally low buttock angles, high flare angles, high open water resistance and high channel resistance coefficients, complement the Phase 2 findings.

5.4 Conclusions

Phase 2 data are only available for the resistance ahead in their own recently broken channels. The data are however more complete, including some information on channel coverage.

It is not possible to draw definitive conclusions from the complete data set. However, a general trend can be seen that non-dimensional channel resistance coefficient generally increases with increase in open water resistance per unit displacement and with decrease in level ice resistance. That is, the most efficient icebreaking forms, which are also generally the least efficient open water forms, have the higher channel resistance coefficient.

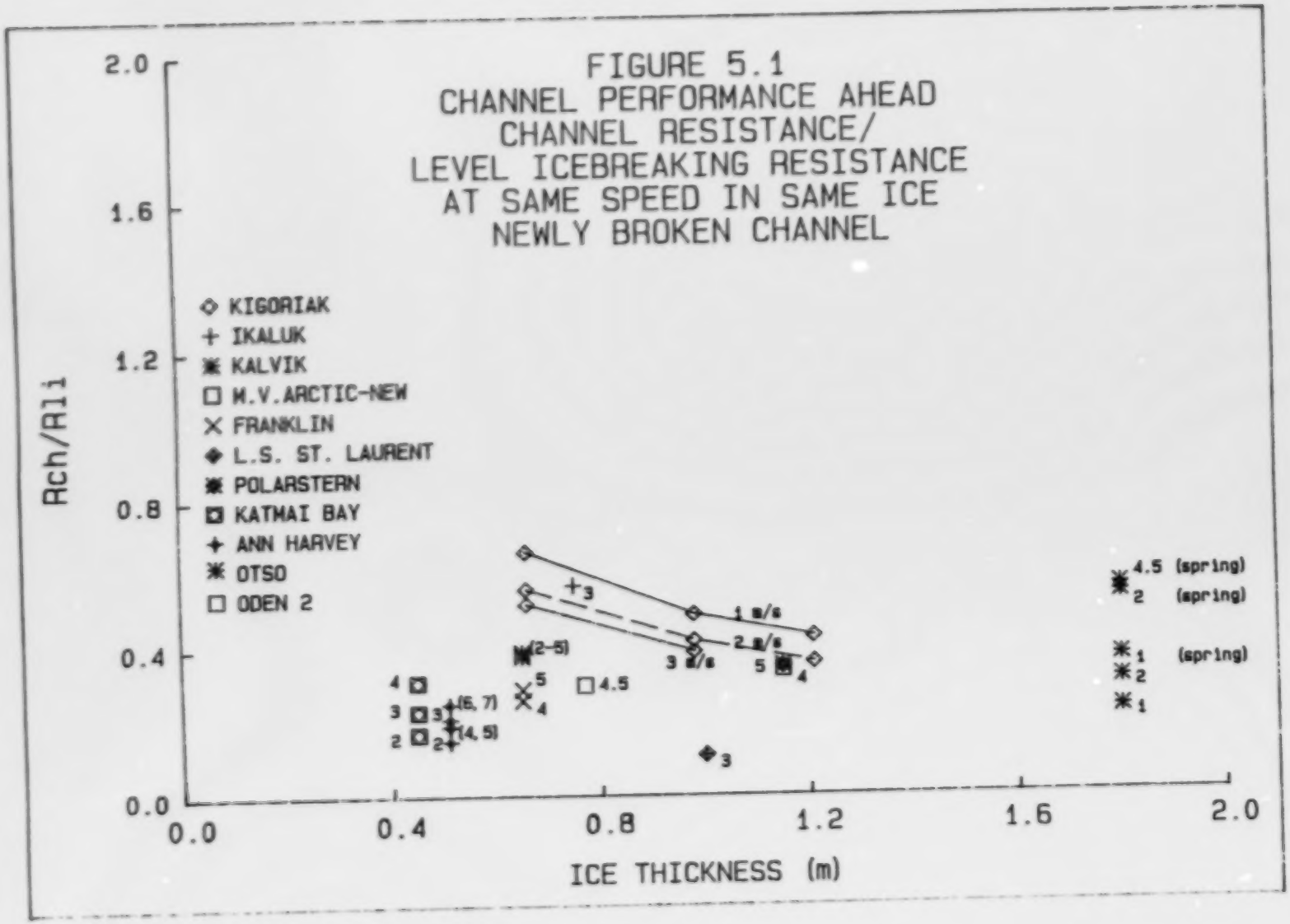


FIGURE 5.1
CHANNEL PERFORMANCE AHEAD
CHANNEL RESISTANCE/
LEVEL ICEBREAKING RESISTANCE
AT SAME SPEED IN SAME ICE
NEWLY BROKEN CHANNEL
Rch/Rli
ICE THICKNESS (m)
2.0
1.6
1.2
0.8
0.4
0.0
0.0
0.4
0.8
1.2
1.6
2.0
KIGORIAK
IKALUK
KALVIK
M.V.ARCTIC-NEW
FRANKLIN
L.S. ST. LAURENT
POLARSTERN
KATMAI BAY
ANN HARVEY
OTSO
ODEN 2
1 m/s
2 m/s
3 m/s
4.5 (spring)
(spring)
(spring)
(2-5)
(6, 7)
(4, 5)
4.5

6.0 MANOEUVRING PERFORMANCE

6.1 Introduction

The available full scale data for vessels in the group allow comparisons to be made for their performance in the following manoeuvres:

- Turning circle ahead
- Breakout of channel ahead
- Captain's or Star manoeuvre

Turning circle diameter is the traditional and simplest way of expressing the ability of a vessel to change its heading. Generally speaking, the smaller the turning circle, the greater the capability to follow the optimum route and avoid difficult or hazardous features while in continuous motion.

When such motion is stopped, either voluntarily or involuntarily, it may be required to back up and change direction ahead by breaking directly out of the broken channel. The relative ability to carry out this manoeuvre enhances general icegoing ability and can compensate for limitations in steady turning ahead.

Where large changes in heading are required within a relatively small space, this can be effected by the Captain's or Star Manoeuvre. Again, ability to effect this manoeuvre enhances icegoing ability and can compensate for limitations in carrying out other manoeuvres.

Taken overall, these three manoeuvres provide a basic measure of a vessel's steering and manoeuvring capabilities as they affect the missions of transit and ice management. In other missions, however, such as escort, additional manoeuvring qualities can become very important. The ability to back in ice under directional control and to move close alongside a beset vessel are two of these.

Except for M.V.Arctic, escort plays an important and often dominant role in the mission profiles of the Phase 2 vessels. Unfortunately, however, ship trials aimed at measuring the ability of the escort vessels to carry out manoeuvres specifically required for the escort role, have not been carried out. Analysis of the vessels' relative abilities in this regard must therefore be based solely on information obtained from the interview process.

6.2 Turning Circle Ahead.

6.2.1 General

Turning circle trials are normally carried out in level

ice at full power and with full rudder, the vessel being in an initially upright condition. Data for such trials, although limited in some cases, are available for most vessels in the Phase 2 group. The exceptions are M.V.Arctic-New (although open water turning is available), and Louis S. St. Laurent. Furthermore, Polar Class data are only available for 20 degrees rudder angle.

Turning may also be enhanced by heeling the vessel and data on this effect are available for M.V.Arctic-Old, Mudyug-New and Oden.

All available and reliable turning circle data for the Phase 2 group of vessels are given in Appendix C, Table 6.2.

The analysis of steady turning ahead in level ice is carried out in exactly the same manner as in Phase 1 of the project. The analysed data from Phase 1 are therefore able to be added directly to the Phase 2 data, forming a data set of some 16 vessels' steady turning performance.

In Phase 1, analysis of turning relative to ship design was limited by the small data set available, and turning performance modelling was only possible for vessels with reamers. The availability of data for 16 vessels, now allows the turning of vessels both with and without reamers to be investigated.

6.2.2 Data Analysis

The preliminary analysis of the turning circle data in level ice and open water, for full or close to full power, is presented in Appendix C, Section 6. In this analysis, the data are non-dimensionalized, as in Phase 1, in the following manner.

* Turning circle diameter is expressed relative to ship waterline length. This allows comparisons to be made between different sizes of ships.

* Ice thickness is expressed as the ratio of the test ice thickness to the icebreaking capability of the vessel at 1 m/s in ice with the test ice properties. These data are obtained from the ice thickness v ship speed data in Section 4.2. Non-dimensionalizing the ice thickness data in this manner is a major step in making the data as independent as is possible of vessel power and environmental conditions. It is roughly equivalent to non-dimensionalizing with respect to speed in the turn, which is considered a significant factor in turning performance. Speed data are only reported in a few cases, such that direct allowance cannot be made.

This approach to non-dimensionalizing the data, however, does not necessarily eliminate all environmental effects between the data. For example, the additional degree of rotation of a vessel in its track due to crushing at the bow and

stern shoulders is not necessarily corrected for ice properties in the same manner as is icebreaking performance ahead.

The non-dimentionalized data are given in Table C6.2 and plotted in Figures C6.2.1 to C6.2.5.

6.2.3 Design Parameters for Comparison.

The non-dimensionalized data are compared below for the effect of design features on level ice turning circle performance. As in Phase 1, this comparison is made at the non-dimensional ice thickness of 60% of 1 m/s icebreaking thickness. These data are interpolated from Appendix C, Figures 6.2.1 to 6.2.5 and given in Table 6.2.3 together with similar data for the Phase 1 vessels.

Table 6.2.3 also includes many design parameters which it is either known or suspected, or have been used formerly in the literature, as having an influence upon turning in ice. These factors are.

* Length of parallel midbody as a percentage of ship length. This is a measure of the degree to which a vessel can rotate freely in its broken track. This parameter was introduced in Phase 1 of the project where it was noted to be a significant parameter. However, insufficient data were available for a detailed analysis.

* Effectiveness of the steering system.

The vessel's ability to turn is clearly related to the magnitude of the rudder side force and turning moment generated by the propeller and rudder arrangement. The number of propellers, whether open or ducted, and number of rudders is listed in Table 6.2.3. When a single or twin rudders lie directly behind a single or twin propellers, the steering system is denoted as fully effective. When a single centreline rudder is positioned behind twin wing propellers or the centre propeller of three equally working propellers, the steering system is denoted as partially effective.

It is clear that this notation is far from precise. The effectiveness of steering systems is clearly dependent upon additional design details, such as shaftline separation, open or ducted propellers and propeller and rudder dimensions as well as trials operating conditions. However, no suitable model is available at present to provide a more accurate measure of steering system effectiveness.

In Phase 1, a turning force coefficient was introduced from Reference 93, in order to provide an indication of steering system effectiveness. The coefficient indicated that Terry Fox, having a single centreline rudder and twin wing propellers (in this study, partially effective), had a lower turning force coefficient than other vessels in the Phase 1 group which all qualify in this study as fully effective.

However, beyond demonstrating the major differences of fully and partially effective steering systems, the turning force coefficient is not considered to add to our understanding of turning data.

The reasons are as follows:

- The turning force coefficient is a measure of the side force on the rudder divided by ship length. However, there is no physical understanding for side force per unit length to be a relevent parameter.

- Rudder side force is treated as a function of the bollard pull at maximum power and the effective rudder area.

However, all ship turning trials are not conducted at maximum power. For ducted screw vessels, up to 40% of bollard pull is provided by the duct. It is the remaining propeller thrust only which represents the propeller race acting on the rudder.

Rudders behind propellers are given an effective area coefficient of 1.0. Others are given a coefficient of 0.5. This does not take into account shaft separation and wake differences between open and ducted propellers.

It is therefore considered that the simple designation of steering systems as either fully or partially effective is the most realistic approach at present.

* Reamer width as a percentage of parallel side.
This is a measure of the degree of rotation of a reamered vessel in its broken track.
It was demonstrated in Phase 1 of the project that this is a governing parameter for vessels with reamers. This study adds two reamered vessels, Mudyug-New and Oden to the data group.

* Midship section side slope angle.
This is thought to aid turning by producing a greater amount of local crushing, bending and ice breaking, thereby allowing the vessel to rotate more in the turn.
Some indications of this effect were noted in Phase 1.

* Ship length/beam ratio.
This factor has for long been considered important for turning.

* Ice flexural strength.

6.2.4 Results

Vessels with Reamers

Non-dimensional turning diameter is plotted versus reamer width per unit parallel side in Figure 6.1, for all reamered

vessels in the combined group. Turning diameter has been corrected to a constant 35 degrees rudder angle.

It is noted that the turning performance of the additional reamered vessels with vertical parallel sides completes very logically and clearly a well defined relationship of decreasing turning diameter with increase in reamer width per unit parallel side.

Conventional Vessels or Vessels without Reamers.

Non-dimensional turning diameter is plotted versus parallel midbody as a percentage of waterline length in Figure 6.2, for all conventional vessels in the combined group. The data are for full rudder angle, except for the Polar Class which have a rudder angle of 20 degrees.

Two curves are drawn on Figure 6.2, one marked Fully Effective and the other Partially Effective steering arrangements. These curves are not intended to be definitive, but to indicate overall observed relationships.

The partially effective curve passes through data for T.Fox and the R-Class. It can also be noted that the Polar Class as a triple screw vessel would also lie on or close to this line, if the data were corrected to full rudder angle.

The fully effective curve passes through data for Arctic Ivik, M.V.Arctic, Otso Class and Mudyug-Old. Polar Class performance as a single screw vessel would also lie on or near this line if the data were corrected to full rudder angle.

These two curves therefore suggest that for nine of the conventional vessels in the group, turning performance in level ice can be described principally in terms of percentage parallel midbody length and effectiveness of the steering arrangement. The results for the remaining two vessels do not however lie on the respective curves. Their relative positions are discussed below.

Design and environmental parameters for the two vessels from Table 6.2.3, are given below.

Vessel	Rudder Effectiveness	Side Slope	Ice Strength
1100	Partial	0	Very Weak
Polarstern	Partial	8	Very Weak

It is noted that both of the vessels' turning trials were conducted in the weakest ice conditions of the full data set. Also, the turning performance of the 1100 vessel, with no side slope, is closer to the nominal performance curve than that of Polarstern with appreciable side slope. Moreover, it is noted from Table 6.2.3 that Polarstern's steering arrangement is different from other vessels in the partially effective group in

that the twin propellers are ducted. The shaftlines are also closer together than other vessels in the partially effective group. The effectiveness of Polarstern's steering arrangement may therefore be appreciably higher than that of other vessels in the group.

The above information for the 1100 and Polarstern suggests that side slope and ice strength may have an important effect upon level ice turning performance and that the simple measure of steering system effectiveness used is not sufficient to differentiate adequately between all vessel designs.

The effect of ship length/beam ratio upon turning performance is investigated in Figure 6.3. Data points for all vessels are plotted and the nominal effectiveness of their steering systems are given. Other than that the six best turning vessels all have fully effective steering arrangements, no general trends can be seen for the effect of length/beam and steering effectiveness upon turning performance in ice. The data show that most icebreakers have similar length/beam ratios but exhibit very different turning abilities.

If the data points for Terry Fox and Arctic Ivik were removed, it might appear that length/beam ratio is a significant factor, since non-dimensional turning diameter increases with increase in length/beam ratio for the cargo icebreaker M.V.Arctic. However, the presence of the Terry Fox and Arctic Ivik data radically alter this interpretation.

Arctic Ivik and Polar Class both have fully effective steering arrangements and the same length/beam ratio, yet the Polar Class turns seven times better. The R-Class and Terry Fox both have partially effective steering systems and the same length/beam ratio, yet the R-Class turns more than two times better. The only way in which such facts can be reconciled and brought into a common understanding with all Phase 1 and Phase 2 turning data is through the presentation with respect to parallel middle body in Figure 6.2.

The physical understanding of relationships in Figure 6.2 is viewed as entirely logical. The percentage length of parallel middle body is a direct measure of the degree to which a vessel may rotate in its broken track, which in turn has a direct effect upon turning diameter. Length/beam ratio on the other hand is only a measure of rotation in the track for vessels within the same general family of shapes.

As has been seen from the analysis above in Figure 6.1 (Reamered vessels) and Figure 6.2 (Conventional vessels), turning performance is clearly more dependent upon local geometry about the waterline than upon overall dimensions of the vessel.

Effect of Heel and Hull Lubrication

The significant effect that heel can have on turning per-

formance was reported in Phase 1 with reference to the reamered vessels Kigoriak and Robert Lemeur. This project provides additional information for the vessels M.V.Arctic (conventional), Mudyug-New (reamered) and Oden (reamered). The data are listed in Appendix C Table 6.2 and plotted in Appendix C Figures 6.2.1 and 6.2.4. The ratios of turning diameter with and without heel, versus heel angle, are plotted for the Phase 2 vessels in Figure 6.4, together with the Phase 1 data.

The new data for Mudyug and Oden lie within the bounds of the Phase 1 data for the other contemporary reamered vessels Kigoriak and Robert Lemeur, while the data point for M.V.Arctic demonstrates an even more significant improvement over upright turning ability. The improvement in turning ability is approximately 30% for Mudyug, 50% for Oden and 60% for M.V.Arctic. The Phase 2 data therefore confirm the major effect which heel can play in turning performance in ice. This applies to conventional as well as reamered vessels.

In terms of non-dimensional turning ability (diameter/length) whilst heeled, it will be noted that Mudyug and M.V.Arctic are very similar, while Arctic's improvement due to heel is much greater. This suggests that the relative improvement which can be achieved in turning is greater for poorer turning vessels. The Oden data point does not follow this trend. However, this vessel improves significantly upon good turning ability through variable geometry in the heeled condition, when a secondary reamer, creating an even wider track, comes into play.

An additional effect on turning is indicated by data for M.V.Arctic in Appendix C, Figure 6.2.1. Use of the bubbler system reduced the turning circle diameter by approximately 50% in thin ice but hardly at all in thick ice. It is interpreted that the bubbler system assists in breaking and clearing a wider track in thin ice but has no such significant effect in thick ice.

6.3 Channel Breakout

This manoeuvre requires the ship to break out of its own freshly broken channel. Full power and rudder are used. The time to turn 90 degrees and the distance required should be recorded. The ship should be stopped at the start of the manoeuvre.

The available results for channel breakout ahead and astern are given in table 6.3.1. It is obvious from the results for both the speed and the change in angle, that there is no common methodology for performing the tests. In fact none of the reports give details of the testing procedures. The results for the time taken for the manoeuvre can not be compared between ships because of the different heading angle changes.

Channel breakouts for the Ann Harvey require a high speed before the ship will breakout. In the thin ice in which the ship was tested, it is suspected that the waves at these speed broke the ice giving the stern room to swing and allowing the bow to breakout. This tends to confirm the interview with the master of the Martha Black (another 1100 class ship), who stated that the ship was difficult to breakout because of the length of the midbody and the shape of the bow. In addition the length of time to initiate the turn is thought to be due to the delay in response to the helm caused by the single centreline rudder and twin screw arrangement.

The Samuel Risley requires speeds greater than 5 knots to breakout. Again the length of the midbody hinders the breakout and the higher speeds are required to break the ice with wave action to allow the stern room to swing. Due to the square stern and the poor astern icebreaking capabilities, the ship is incapable of an astern breakout.

The Arctic requires a long time and high speeds to achieve very small changes in heading angle during breakout. Again the long length of midbody prevents breakout until sufficient speed has been achieved to break the ice giving the stern room to swing.

The Mudyug responds immediately to the helm because of the twin rudder/twin screw arrangement and the ability of the stern to swing due to the wider track created by the reamers.

The channel breakouts of the Oden demonstrate the dramatic reduction in time to achieve a change in heading angle of 90 degrees with an angle of heel of 7 degrees. The time is more than halved (45 seconds versus 100 seconds). The angle of 7 degrees allows the turning reamer to contact the ice. The ship will breakout astern despite the square stern shape. The progress is very slow even with the assist of heel and the bow thruster.

6.4 Captain's Manoeuvre (Star Turn)

For most icebreakers this manoeuvre is an alternative to the turning circle as it requires a smaller space to effect a change in direction of 180 degrees. It involves turning while using a succession of ahead and astern manoeuvres.

The available results are given in table 6.2 and plotted in figure 6.5 where results are compared to those of the Kigoriak from the phase 1 study.

The results follow the same general trend as the phase 1 study, i.e., an exponential increase in time for increasing ice thickness. The effect of the length of parallel midbody (with no reamers) is clearly shown by the greater times of the Harvey and Risley when compared with the Kigoriak. This effect of the

midbody length (coupled with low power to displacement ratio) is shown dramatically by the extremely long times taken by the Arctic.

The time taken for the Oden is less than the Kigoriak in a comparable ice thickness. Without heel the time to turn 180 is shorter than for the Star manoeuvre. With heel the time is about half the time for the Star manoeuvre. The space required for the turn ahead with heel is about 260 metres, a distance less than that required for a Star manoeuvre on the Harvey in thinner ice. For the Oden, a turn with heel is the most efficient way of achieving a 180 degree change of heading even in a restricted space.

6.5 Conclusions

The turning circle data for the Phase 2 vessels have been presented in the same non-dimensional format as for the Phase 1 vessels, and the combined data set has been used to investigate the effect of icebreaker design features on turning ability in level ice.

Additional Phase 2 information for vessels with reamers has confirmed that non-dimensional turning diameter is dependent strongly upon the ratio of reamer width to length of parallel side, turning diameter decreasing predictably with increase in this ratio. For reamered vessels with vertical parallel sides, a minor modification only of the turning model developed in Phase 1 is required in order to describe the performance of all vessels in the expanded group.

As a result of the many data in Phase 2 for conventional vessels without reamers, it has been possible to extend the turning analysis in Phase 1 and determine the most important parameters affecting their turning performance.

The non-dimensional turning performance of conventional vessels in level ice is shown to be strongly dependent upon the ratio, length of parallel waterline/waterline length, and upon the effectiveness of the steering arrangement or location of the rudder(s) relative to the propeller(s). Turning performance is enhanced by decrease in the length of parallel side and increase in steering system effectiveness.

Other factors indicated as having possible important effects are side slope angle and ice strength, although it has not been possible with the data set available to quantify their individual effects.

Ship length/beam ratio appears to have no significant effect upon non-dimensional turning performance, performance being clearly more dependent upon local geometry about the waterline than upon overall dimensions of the vessel.

Further analysis of the data is possible but would require an improved definition or algorithm for the effectiveness of steering arrangements as they relate to turning in ice.

The additional data for the Phase 2 group of vessels confirm the significant effect which heel can have on the turning performance of both reamered and conventional vessels. Bubbler systems can improve turning in thin ice, but not in thick ice.

To enable valid comparisons between the channel breakout capabilities of ships, a standard procedure should be adopted. The procedure would include requirements for proper documentation of the results and the environmental conditions associated with the trial. The longer the length of parallel midbody (with no reamer), the more difficulty in breaking out of a channel particularly in thick ice where speeds are limited. Angle of heel can be used to advantage in achieving fast channel breakouts.

Star manoeuvre times increase exponentially with increasing ice thickness and increase with length of parallel midbody. For ships with superior ahead turning capabilities and relatively poor astern manoeuvrability, a 180 degree turn ahead can be faster than a Star manoeuvre, particularly if heel is employed.

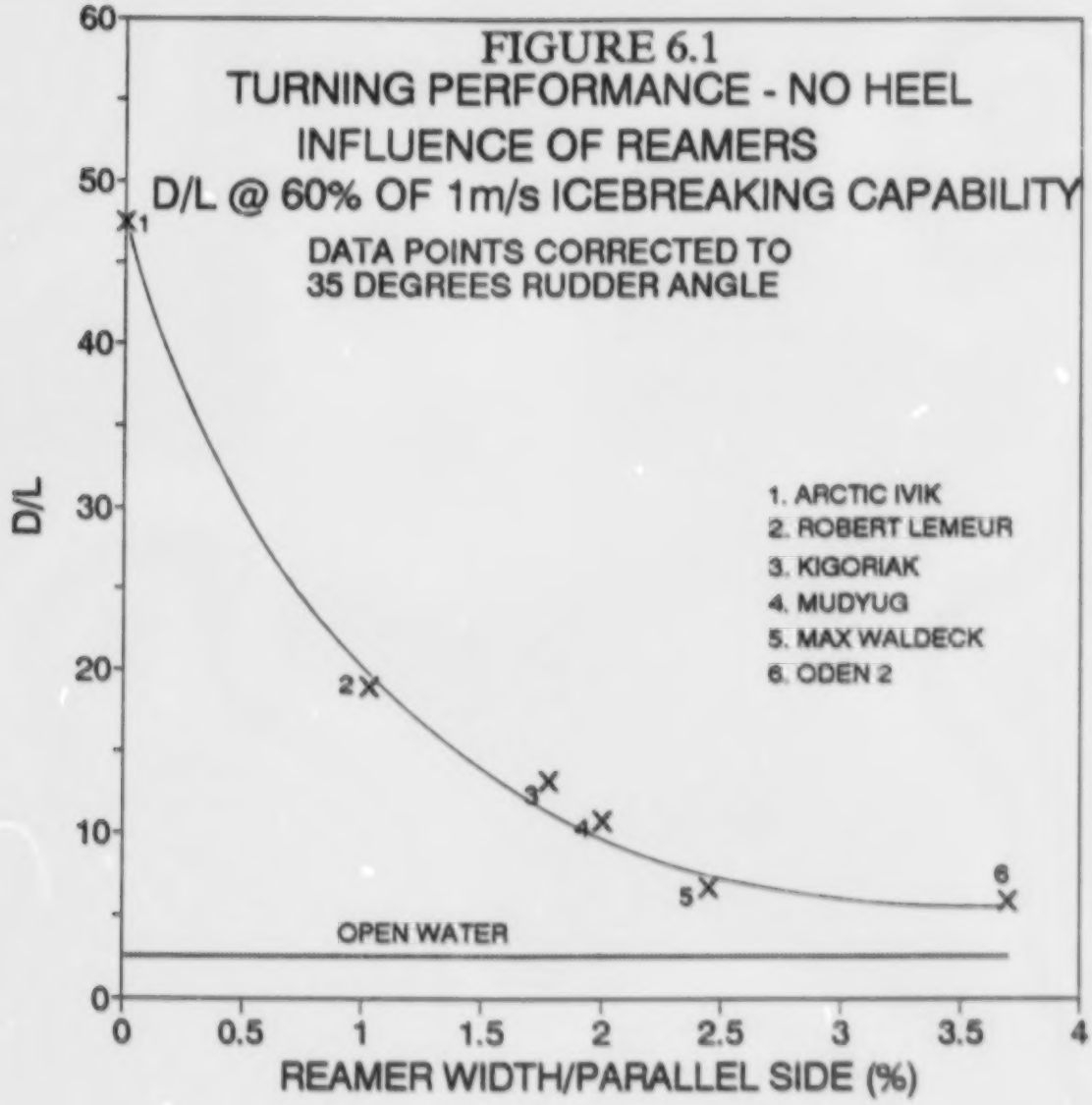


FIGURE 6.1
TURNING PERFORMANCE - NO HEEL
INFLUENCE OF REAMERS
D/L @ 60% OF 1m/s ICEBREAKING CAPABILITY
DATA POINTS CORRECTED TO
35 DEGREES RUDDER ANGLE
1. ARCTIC IVIK
2. ROBERT LEMEUR
3. KIGORIAK
4. MUDYUG
5. MAX WALDECK
6. ODEN 2
OPEN WATER
D/L
REAMER WIDTH/PARALLEL SIDE (%)
0
10
20
30
40
50
60
0
0.5
1
1.5
2
2.5
3
3.5
4

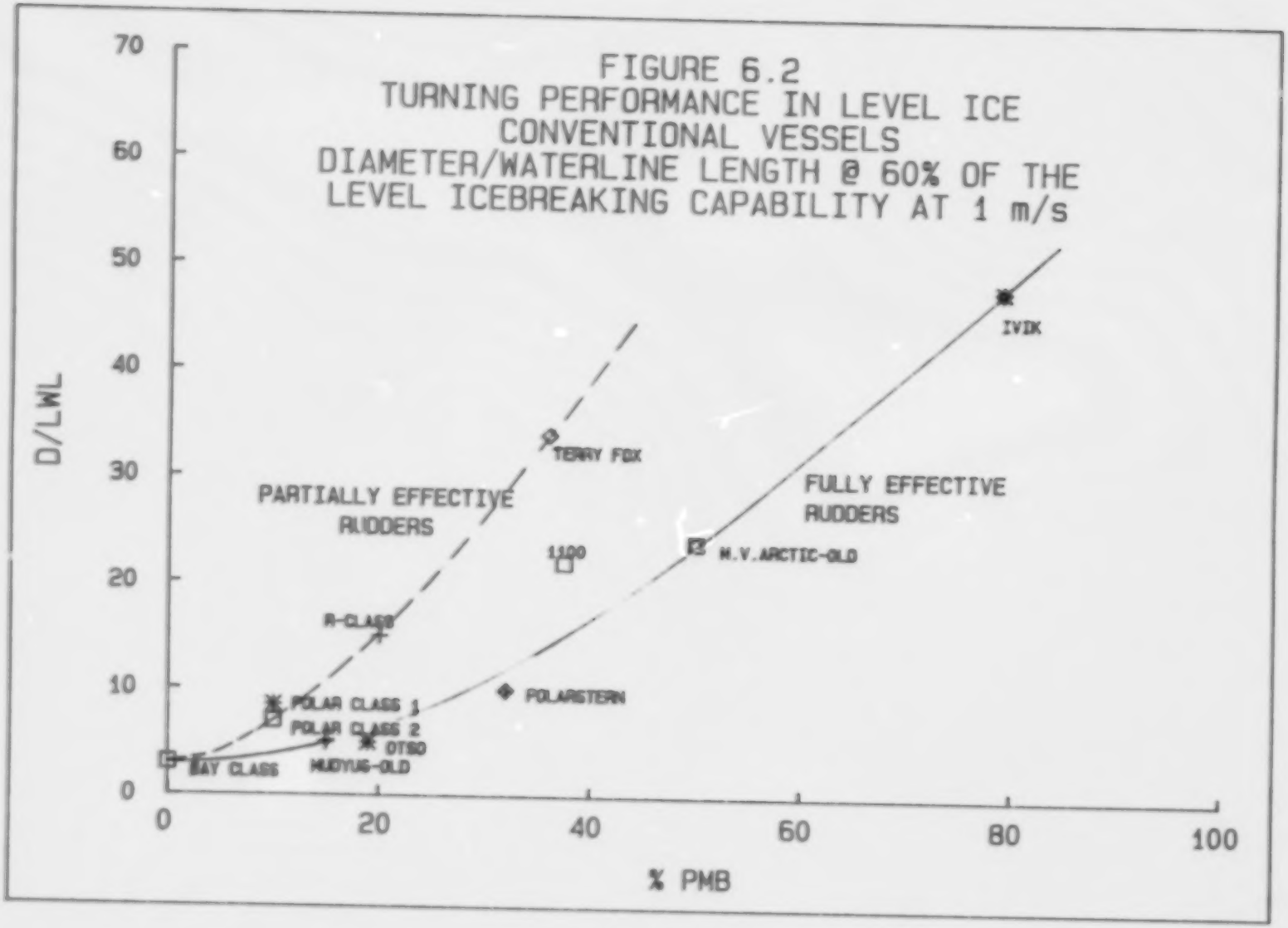


FIGURE 6.2
TURNING PERFORMANCE IN LEVEL ICE
CONVENTIONAL VESSELS
DIAMETER/WATERLINE LENGTH @ 60% OF THE
LEVEL ICEBREAKING CAPABILITY AT 1 m/s
D/LWL
% PMB
0
10
20
30
40
50
60
70
0
20
40
60
80
100
PARTIALLY EFFECTIVE
RUDDERS
FULLY EFFECTIVE
RUDDERS
TERRY FOX
1100
M.V. ARCTIC-OLD
IVIK
R-CLASS
POLAR CLASS 1
POLAR CLASS 2
OTSO
BAY CLASS
MUDYUG-OLD
POLARSTERN

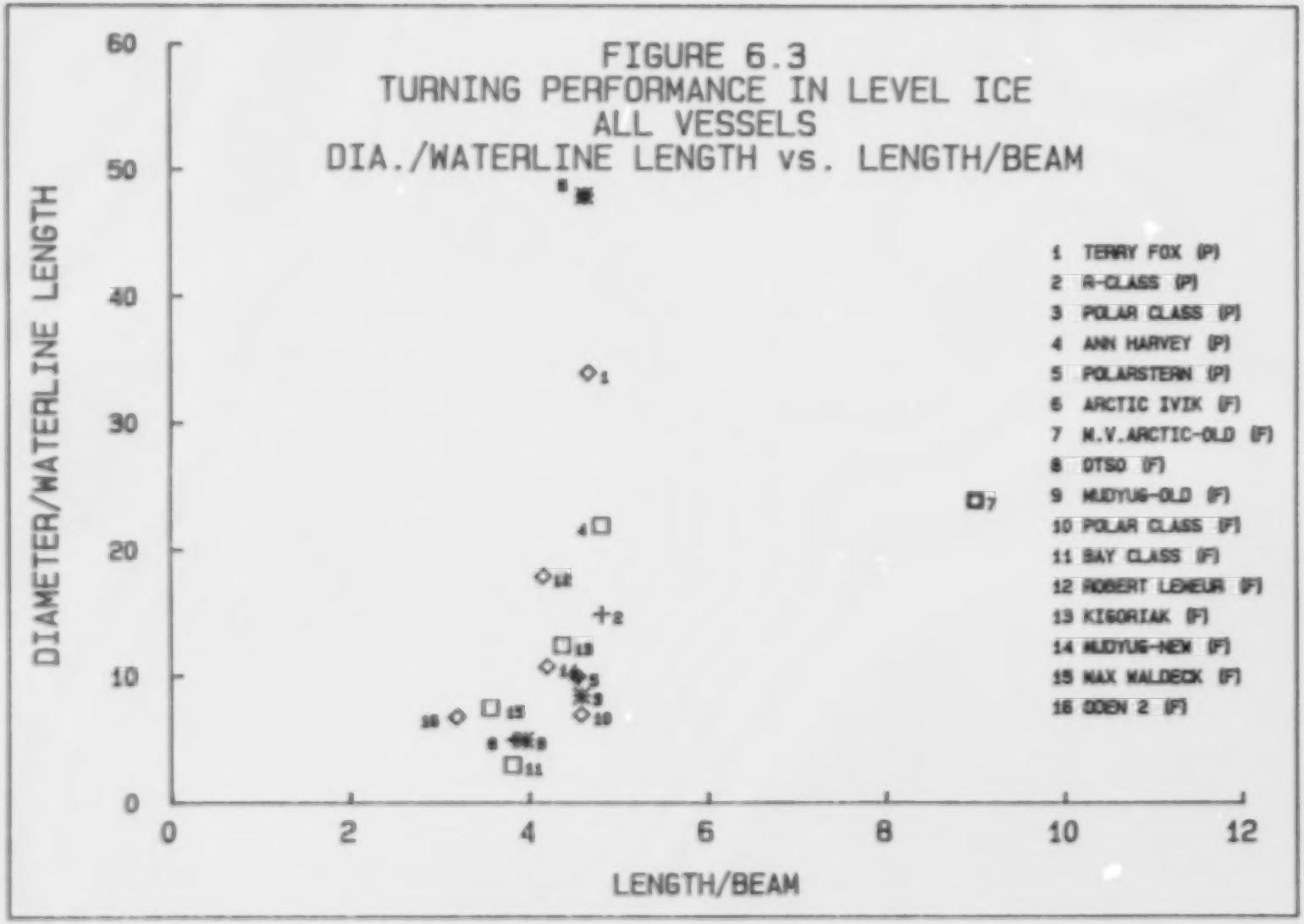


FIGURE 6.3
TURNING PERFORMANCE IN LEVEL ICE
ALL VESSELS
DIA./WATERLINE LENGTH vs. LENGTH/BEAM
DIAMETER/WATERLINE LENGTH
LENGTH/BEAM
0
10
20
30
40
50
60
0
2
4
6
8
10
12
1 TERRY FOX (P)
2 A-CLASS (P)
3 POLAR CLASS (P)
4 ANN HARVEY (P)
5 POLARSTERN (P)
6 ARCTIC IVIK (F)
7 M.V.ARCTIC-OLD (F)
8 OTSO (F)
9 MUDYUG-OLD (F)
10 POLAR CLASS (F)
11 BAY CLASS (F)
12 ROBERT LEMEUR (F)
13 KIGORIAK (F)
14 MUDYUG-NEW (F)
15 MAX WALDECK (F)
16 ODEN 2 (F)

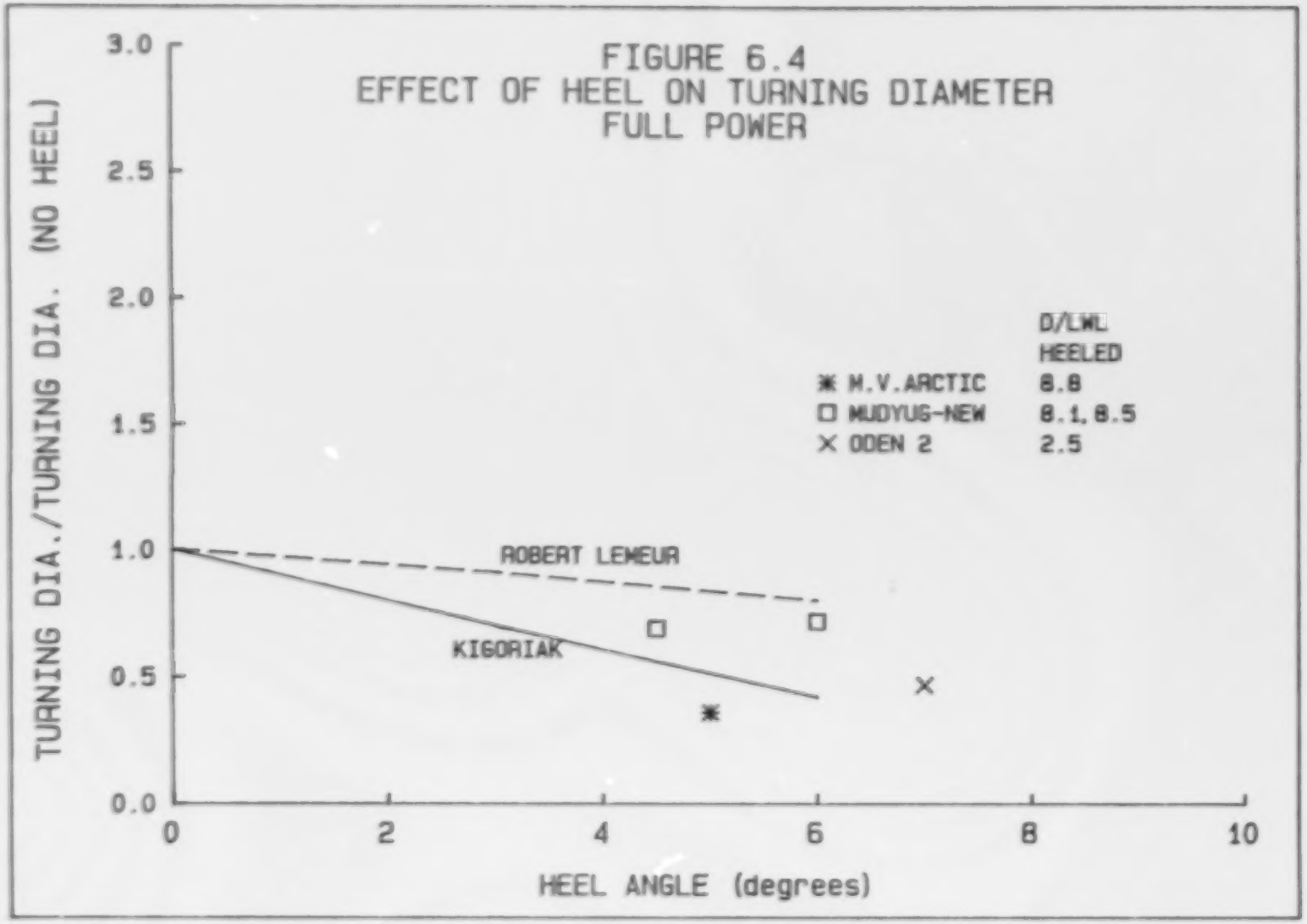


FIGURE 6.4
EFFECT OF HEEL ON TURNING DIAMETER
FULL POWER
TURNING DIA./TURNING DIA. (NO HEEL)
3.0
2.5
2.0
1.5
1.0
0.5
0.0
0
2
4
6
8
10
HEEL ANGLE (degrees)
D/LWL
HEELED
M.V.ARCTIC 8.8
MUDYUG-NEW 8.1, 8.5
ODEN 2 2.5
ROBERT LEMEUR
KIGORIAK

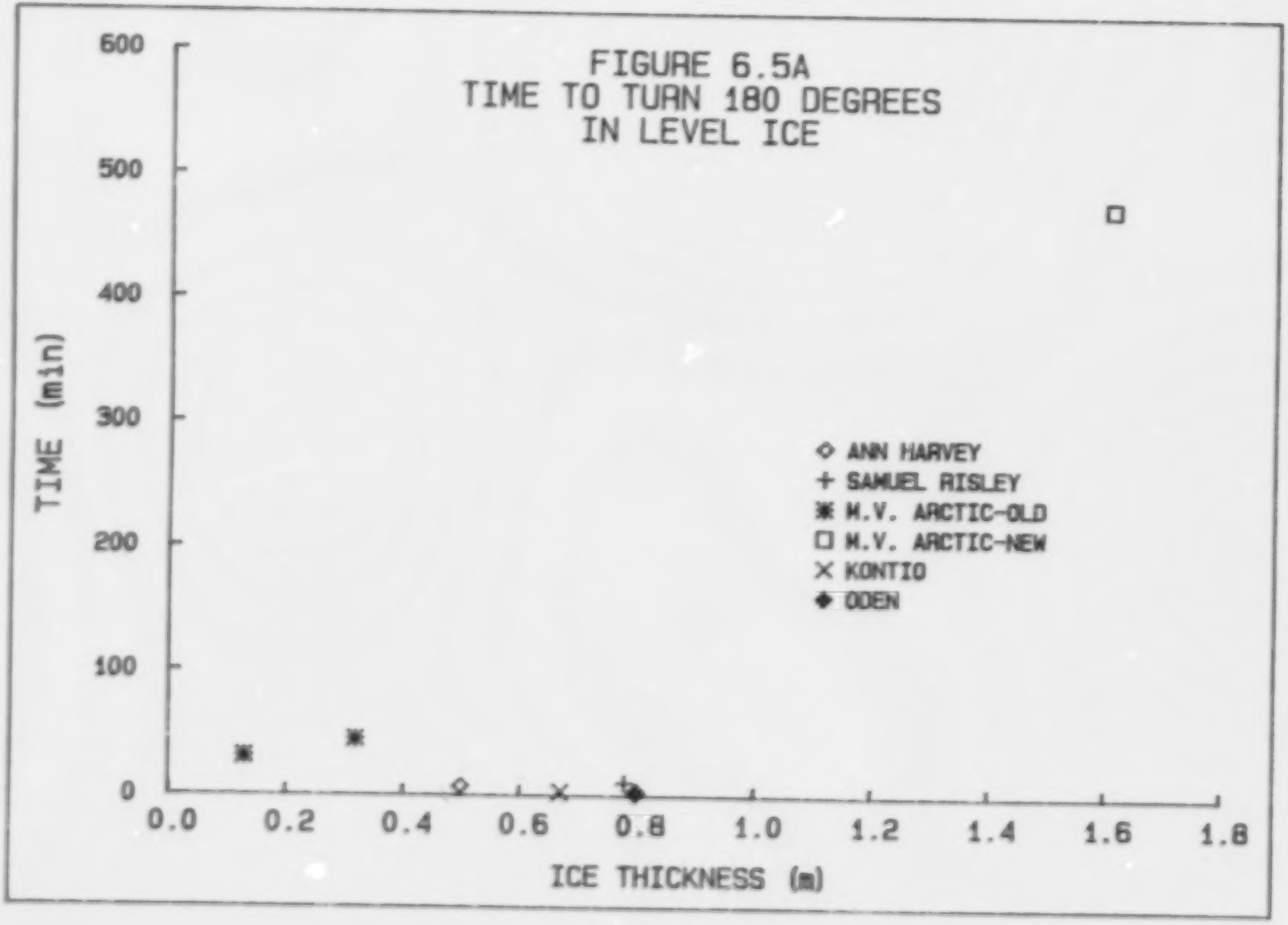


FIGURE 6.5A
TIME TO TURN 180 DEGREES
IN LEVEL ICE
TIME (min)
600
500
400
300
200
100
0
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
ICE THICKNESS (m)
ANN HARVEY
SAMUEL RISLEY
M.V. ARCTIC-OLD
M.V. ARCTIC-NEW
KONTIO
ODEN

FIGURE 6.5B
TIME TO TURN 180 DEGREES
IN LEVEL ICE

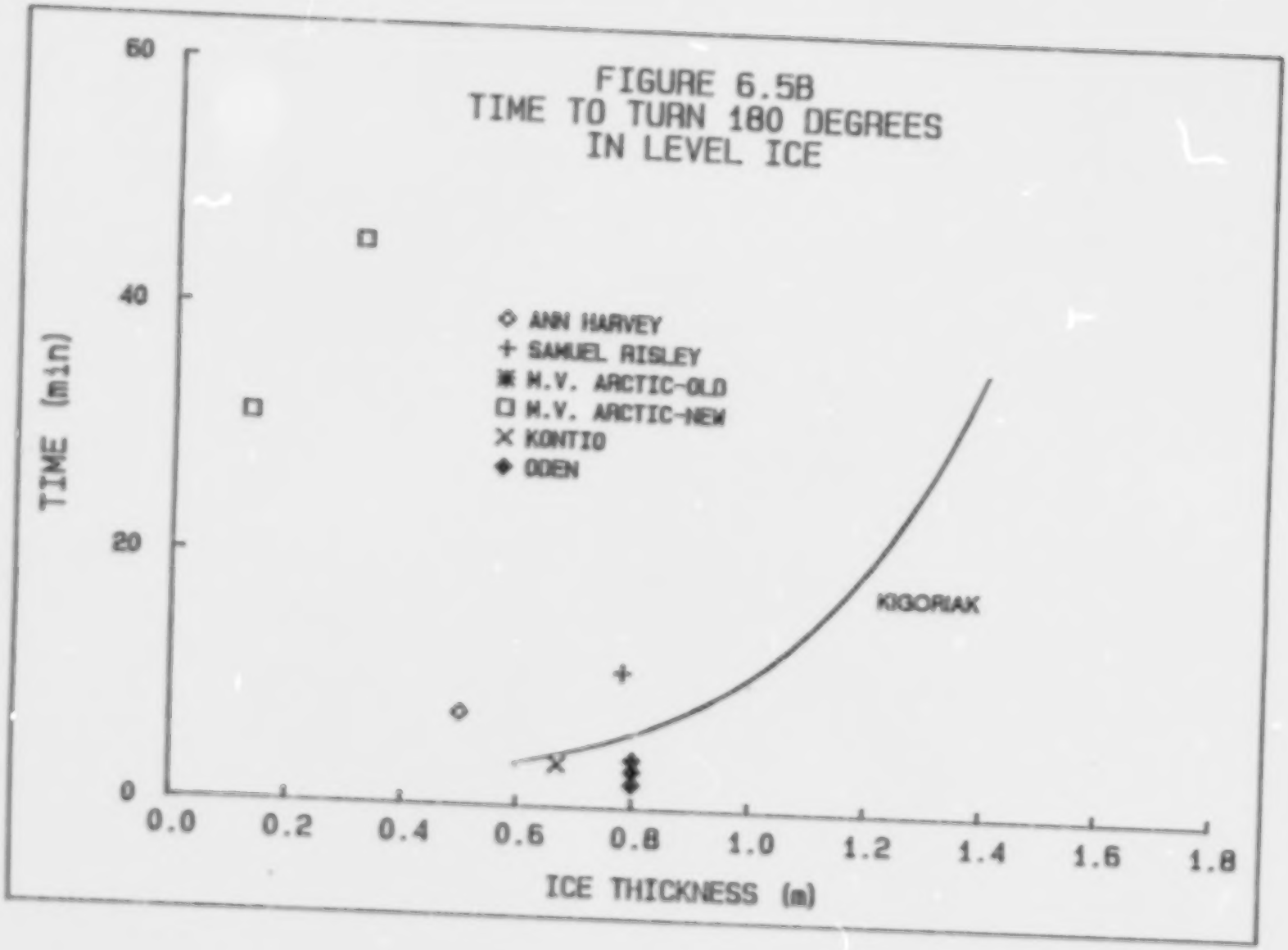


TABLE 6.1
STEADY TURNING IN ICE
SHIP AND ENVIRONMENTAL PARAMETERS

VESSEL	DWT	PWR %	HEAVES H	HEAVES/ PROP-S	L/B	SIDE SLOPE DEGREES	PROP/ RUDDERS	STEERING EFFECTIVENESS	FLEX STRENGTH
N.V.ARCTIC-ICE	24.0	50.0			9.00	0	1D/1	FE	INTERMEDIATE
POLAR CLASS	7.0	10.0			4.58	12	1/1	FE	WEAK
	8.5	18.0			4.58	12	3/1	FE	WEAK
R-CLASS	15.0	28.0			4.85	5	2/1	FE	STRONG
POLARSTERN	10.0	32.0			4.54	0	2D/1	FE	VERY WEAK
ROBYSO-ICE	5.0	19.0			3.95	0	2/2	FE	N/A
ROBYSO-MED	10.8	59.0	1.1	2.08	4.20		2/2	FE	STRONG
TYPE 1100	22.0	37.5			4.85	0	2/1	FE	VERY WEAK
DAY CLASS	3.0	8.0			3.81	20	1/1	FE	STRONG
0750	5.0	15.0			3.83	10	2/2	FE	INTERMEDIATE
ESSO 2	6.0	63.7	2.2	3.69	3.19	0	2D/2	FE	INTERMEDIATE
KIGORIAK	12.5	44.5	1	1.79	4.37	0	1D/1	FE	INT/STRONG
LOMEHR	18.0	63.2	0.5	1.05	4.16	0	2D/2	FE	INT/STRONG
T POE	34.0	36.0			4.66	0	2/1	FE	INT/STRONG
ZYDE	48.0	79.0			4.62	0	2D/2	FE	INT/STRONG
MV.LOUIS	7.5	44.4	0.77	2.40	3.56	0	1D/1	FE	INT/STRONG

TABLE 6.2

OTHER MANEUVERS

SHIP	ICE THK. M	STAR TYPE	STAR HD KNH KEH	STAR DIMENSIONS M	STAR COMMENTS	CHANNEL BOUT ICE THK M	CHANNEL BOUT VEL KTS	CHANNEL BOUT TURN DIR	CHANNEL BOUT T S	CHANNEL BOUT HDING DEG	CHANNEL BOUT CRSE TOT S	CHANNEL BOUT TIME S	CHANNEL BOUT COMMENTS
ANN HARVEY	0.53 + .10 SNOW					0.53 + .10 SNOW	10.1	S	9	68	59		ANNIES BROKE ICE
		7.53	5	300 X 300	SPLIT SHAFTS		11.6	P	6	87	50		
		8.16	4	300 X 300	USED ASTERN		11.0	P	7	47	47		
		6.50	3	300 X 300			8.4	S	10	43	61		
SAMUEL RISLEY	0.75 + .05 SNOW		6	110 X 315		0.75 + .05 SNOW	15.0						ASTERN BOUT
		11.00	8	190 DIA	SPLIT ASTERN								NOT SUCCESSFUL
				130 X 190									
			6	160 DIA									
ARCTIC (OLD)	0.13	21.23		200 DIA									
	0.32	45.30		600 DIA									
ARCTIC (NEW)	1.05 + .32 SNOW	88.00	12		30 DEG ONLY	0.85 + .13 SNOW		S		29	295		6.4 KTS MAX V
	1.55 + .12 SNOW	396.00	70		150 DEG ONLY	0.85 + .13 SNOW		S		23	180		7.0 KTS MAX V
						0.85 + .13 SNOW		S		18	147		7.2 KTS MAX V
						0.90 + .15 SNOW		S		20	261		10.0 KTS MAX V
						0.90 + .15 SNOW		S		19	279		6.4 KTS MAX V
						0.90 + .15 SNOW		S		24	210		7.4 KTS MAX V
ENDEAVOR	1.05 TO 1.32			250 DIA		1.01 + .13 SNOW		P	0				
KONTIO	0.67 + NO SNOW	3.50			3 KEH SCISSOR								
ODEN	0.70 + .20 SNOW	3.90	3		STAR MAN. FROM CHANNEL	0.70 + .20 SNOW	6.7	S		90	100		WATER LUB ON
								S		90	45		NL ON, 7 DEG HEEL
					2.40 KEH		4.4	S		54	240		AST, THRUST, 7 HEEL
					180 TURN IN		4.4	S		23	330		AST, THRUST
					LEVEL ICE,		6.0	S		10	349		AST (TERMINATED)
					HEEL 7 DEG		4.4	P		45	175		AST, THRUSTER
					2.00 KEH								
					NO HEEL,								
					3.05 KEH								
					ASTERN TURN								
					NOT SUCCESS								
					OUTMANEUVRE								
					3.31 KEH								

7.0 OPEN WATER RESISTANCE

7.1 General

Open water performance data of speed versus shaft power, shaft thrust or resistance for calm water conditions are available for all Phase 2 vessels except M.V.Arctic-Old. The data are analysed and presented in the same format as in Phase 1, with speed non-dimensionalized in terms of Froude Number and resistance presented per unit tonne of displacement. Parametric influences are discussed and comparisons made with the Phase 1 results.

Seakeeping tests have not been carried out on any of the vessels in the Phase 2 group. General seakeeping ability was however addressed in the operator interviews and assessments from the questionnaire are given in Chapter 3.

7.2 Data Analysis

The open water performance data for the Phase 2 vessels are listed in Appendix Tables C 7.2 to 7.12. In the cases of Polar Star, Louis S.St.Laurent and Bay Class, the tables include both model and full scale data. For all other vessels, the data are wholely from full scale trials.

Where resistance is not given directly, it is calculated from shaft thrust using the appropriate thrust deduction or from shaft power using specific net thrusts derived in Section 4.4. For the purposes of data comparison, resistance is presented as in Phase 1 in terms of the specific resistance coefficient, resistance/displacement (newtons/tonne). Speed is expressed in terms of the non-dimensional speed-length ratio Froude Number.

The specific resistance curves are shown, together with the Phase 1 data, in Figures 7.1 and 7.2.

7.3 Results

Except for the Oden and Mudyug-New, the Phase 2 open water performance data are all for fully formed, smooth curved or hulled, icebreakers. Oden, having reamers and chines, is within the Phase 1 family of hulls and is therefore compared with them in Figure 7.1. Mudyug-New has a contemporary bow form with reamers attached to a conventional mid and afterbody. This vessel is included in the contemporary group in Figure 7.1.

In Phase 1, it was determined that results for the contemporary, chined hull family, formed a logical set of curves in which specific resistance increased with increase in Froude number and block coefficient and decreased with vessel size. It

is seen in Figure 7.1, that Oden's data fall very logically within this same family. Oden, with a displacement almost twice that of Kigoriak and Terry Fox and a similar block coefficient of 0.53, has a resistance coefficient of approximately 60% of their values. The resistance coefficient for Mudyug-New, however, with a block coefficient of 0.56 and a displacement of 7744 tonnes, is similar to that for Oden at 12090 tonnes, or about 25% lower than would be expected for a true contemporary form. It is judged that this relatively lower resistance is probably due to its more hydrodynamic, conventional, mid and afterbody form.

Specific resistance curves for the fully formed hulls are given in Figure 7.2, together with a Phase 1 reference curve for Kigoriak.

It is noted that, except at the very highest speeds, the specific resistances lie within a band which is between 25% and 50% of Kigoriak's, although the Phase 2 group contains vessels of smaller displacement and higher block coefficient than Kigoriak. It is clear that the features of the contempory hull forms, such as reamers, chines and wedges add appreciably to open water resistance. Comparing the R-Class at 6500 to 7500 tonnes with Kigoriak at 6600 tonnes, it is seen that the contemporary hull features increased open water resistance by an average 100%.

In order to determine parametric influences upon the resistances of the fully formed hulls, the following vessel particulars are tabulated in the order of vessel size.

Vessel	Dislpt. tonnes	Block coeff.	Length/ beam	Beam/ draft
Bay Class	660	0.43	3.8	2.9
Ann Harvey	4346	0.62	4.8	3.0
Mudyug-Old	6211	0.59	4.0	3.1
Radisson	6450	0.62	4.8	2.9
Franklin	7660	0.62	4.8	2.9
Otso	7950	0.46	3.8	2.9
Larsen	8225	0.61	4.9	2.9
Polar Star	13190	0.62	4.6	2.8
Louis S.St.L	13500	0.56	4.4	2.7
Polarstern	15000	0.53	4.5	2.3
M.V.Arctic	38900	0.71	9.3	2.1

The variations of vessel size and proportions are such as to prevent a direct simple comparison of all vessels at the same time. They are therefore considered in groups.

The group of Polar Star, Louis S.St.Laurent and Polarstern are of approximately similar size and proportions. Resistance per tonne displacement for Polar Star and Louis S.St.Laurent

are two of the lowest in the Phase 2 group, as one would expect for such relatively large vessels. Yet the resistance coefficient for Polarstern is 50-75% higher and only a little lower than that for Oden, of similar displacement but in the contemporary group. The probable reason for Polarstern's seemingly unusually high resistance is not apparent in the form coefficients, but can be seen in the details of the hull form itself (Appendix A). Polarstern is relatively deeper than Polar Star and Louis S.St.Laurent and incorporates a large wedge faired in to the forebody. In some respects it could be considered a hybrid between the conventional and contemporary forms. This large wedge is considered the probable reason for Polarstern's relatively high open water resistance.

The Bay Class are small vessels with low length/beam ratio. These factors might point to a relatively high resistance coefficient instead of the relatively low values measured. The reason is probably due to the block coefficient, which is very low at 0.43.

Otso is similar in displacement to the R-Class vessels yet has a significantly lower specific resistance. The reason is probably the same as for the Bay Class, that of a low block coefficient of 0.46.

M.V.Arctic has a very high displacement and high length/beam ratio. These factors point to a low resistance. Resistance per tonne displacement is not however the lowest in the group, probably due to the relatively high block coefficient of 0.71.

The remaining vessels are Ann Harvey, Mudyug-Old, and the R-Class vessels Radisson, Franklin and Larsen. These vessels have similar form coefficients, although Ann Harvey has only two thirds of the others' displacement. This would suggest a higher resistance coefficient for Ann Harvey, although the reverse is true. The reason for Ann Harvey's unusually low resistance has not been determined

The resistance coefficients for the R-Class are now compared with those of the larger vessels of fairly similar form coefficient, Polar Star and Louis S.St.Laurent. This demonstrates that, as in Phase 1, resistance per unit tonne displacement increases with decrease in displacement.

7.4 Conclusions

The calm water specific resistance for the contemporary icebreaker Oden falls logically within the data set of Phase 1. This confirms the findings that specific resistance for the contemporary family of icebreaker hull forms, incorporating reamers, chines and wedges, increases with Froude number and block coefficient and decreases with vessel size.

The Phase 2 data for conventional, fully formed hulls are much lower than the contemporary hull data. Specific resistance for a conventional vessel can be as low as 50% of a contemporary vessel of the same size and proportions.

Within the conventional group, the same overall parametric trends found for the contemporary hulls, of specific resistance increasing with increase in Froude number and block coefficient and decrease in vessel size, have been noted. However, among fully formed vessels of similar size and proportions, significant differences in resistance, attributable to hull form features, can occur. Specifically it is noted that fully formed vessels which incorporate contemporary type features, can experience similar calm water resistance penalties as a contemporary hull vessel.

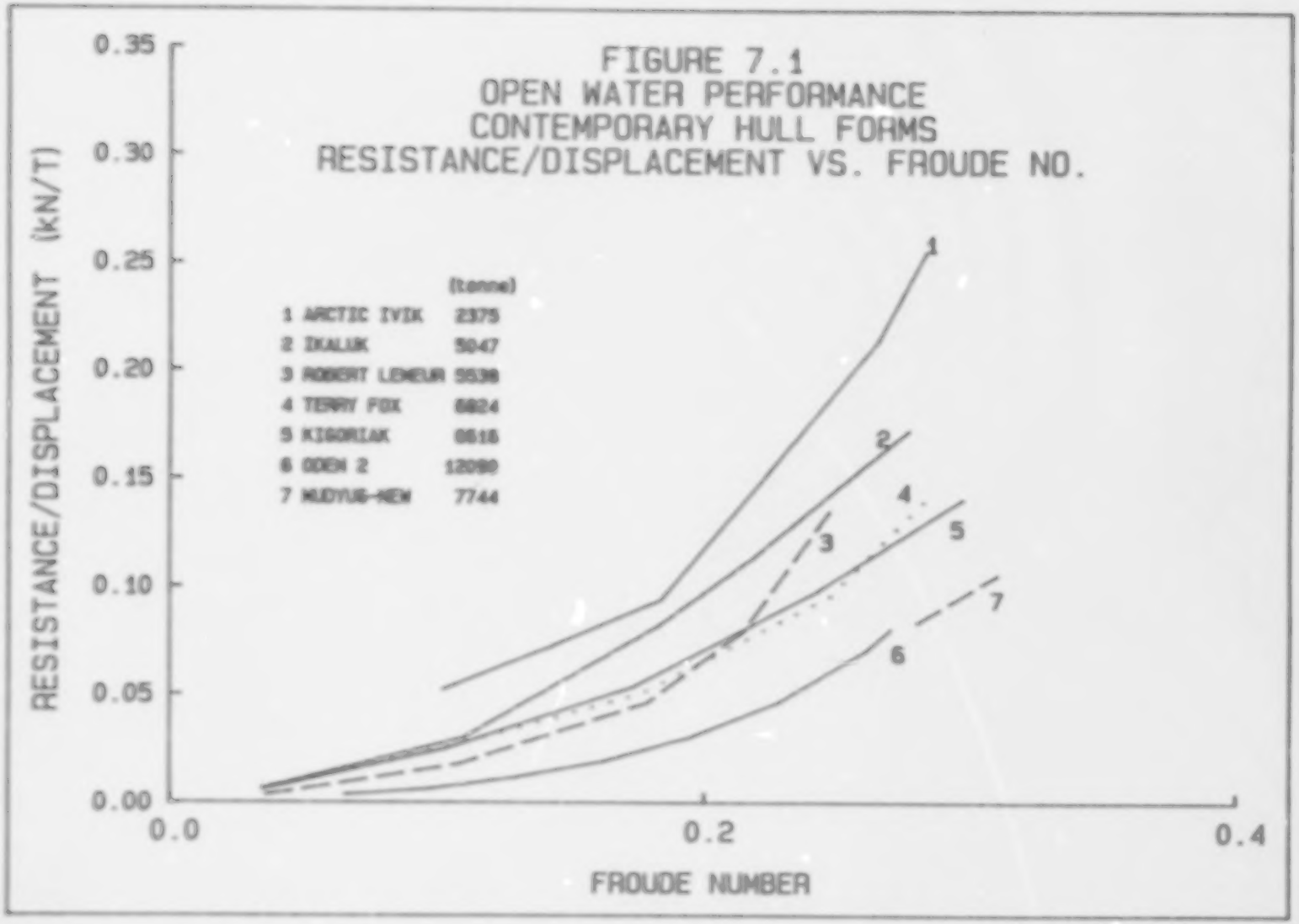


FIGURE 7.1
OPEN WATER PERFORMANCE
CONTEMPORARY HULL FORMS
RESISTANCE/DISPLACEMENT VS. FROUDE NO.
RESISTANCE/DISPLACEMENT (kN/T)
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
0.0
0.2
0.4
FROUDE NUMBER
(tonne)
1 ARCTIC IVIK 2375
2 IKALUK 5047
3 ROBERT LEMEUR 5538
4 TERRY FOX 6824
5 KIGORIAK 8818
6 ODEN 2 12080
7 MUDYUG-NEW 7744
1
2
3
4
5
6
7

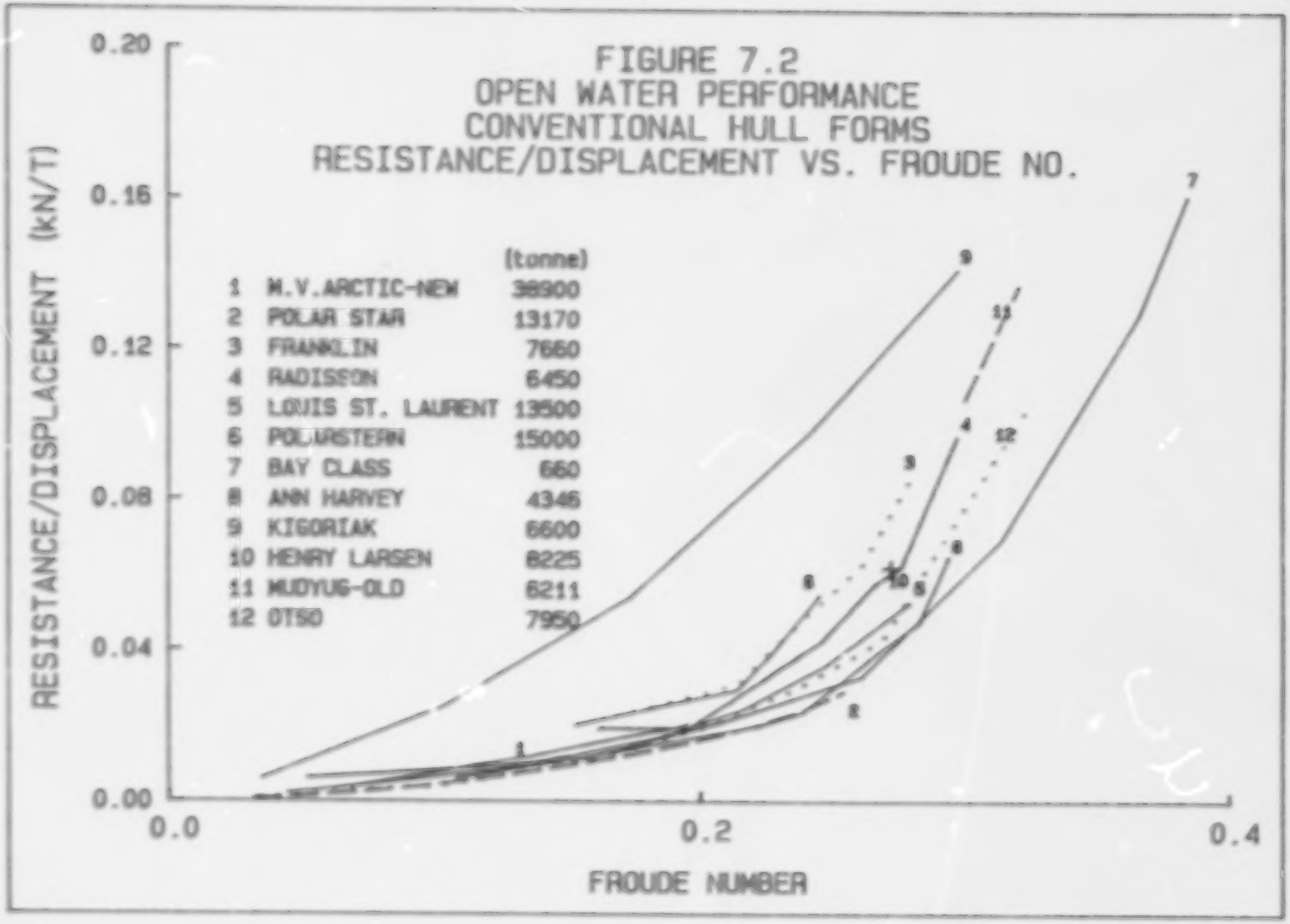


FIGURE 7.2
OPEN WATER PERFORMANCE
CONVENTIONAL HULL FORMS
RESISTANCE/DISPLACEMENT VS. FROUDE NO.
RESISTANCE/DISPLACEMENT (kN/T)
FROUDE NUMBER
0.00
0.04
0.08
0.12
0.16
0.20
0.0
0.2
0.4
(tonne)
1 M.V.ARCTIC-NEW 38900
2 POLAR STAR 13170
3 FRANKLIN 7660
4 RADISSON 6450
5 LOUIS ST. LAURENT 13500
6 POLARSTERN 15000
7 BAY CLASS 660
8 ANN HARVEY 4346
9 KIGORIAK 6600
10 HENRY LARSEN 8225
11 MUDYUG-OLD 6211
12 OTSO 7950

8. RAMMING PERFORMANCE

8.1 Introduction

When a ship is operating in ice thicknesses or conditions beyond its maximum continuous icebreaking capability, it must resort to ramming. The ice conditions may be level ice, ridges or rubble fields. Once ramming is necessary, the average speed drops. The average speed when ramming is a function of both the environmental conditions and the ship's performance capabilities. The environmental conditions include:

- thickness of the level ice (or the ice in the approach channel for ridges)
- width and depth of the ridge or rubble field profile
- degree of consolidation in ridges and rubble fields
- ice block size

The ship's performance capabilities depend upon:

- speed ahead and astern in the broken ice in the approach channel (hull form and power used)
- power/displacement ratio (acceleration)
- extraction ability

Ramming performance in the present study consists of ramming in two different ice regimes; level ice and ridges.

Both are similar in that a single ram for each consists of the following segments;

- acceleration, from start ahead to impact
- penetration, from impact to stopped
- extraction, from stopped to start of astern movement
- backing, from start of astern to stopped

Testing of level ice ramming was conducted on both the Arctic [4,13] and the Louis S. St. Laurent [65]. The resistance calculated from these rams during the penetration phase should extend the ice thickness/resistance curves beyond the range determined from the continuous level ice testing. The results were however inclusive. Data from these tests do however provide ram cycle times which include some information on times for the acceleration, penetration, extraction and backing phases. Penetration distances were also recorded.

Ramming trials were conducted on the Franklin in Lake Melville [57] in both ridges and rubble fields. Although thicknesses were recorded along the ship's route, they were not correlated with individual rams nor were ridge profiles measured. The data do contain information on the ram cycle times and penetration distances.

Ridge ramming trials were conducted on the Polar Star

[37,38], Polarstern [68], Oden [81] and the Otso 80]. These trials recorded ship speeds and distances during the ridge penetrations. In addition the ridge profiles were documented. Calculations can therefore be made on the energies, resistances and ridge cross sectional properties during the penetration phase. This enables comparisons to be made between the ships and in addition with the Phase 1 ships. No data were recorded in these tests on the ram cycle times.

8.2 Ridge Resistance and Penetration Energy

8.2.1 General

The background of the theory and methodology used in this section are given in [83,84,85].

The energy it takes to penetrate a ridge is an important input into the determination of the ship's operational capabilities. Knowing the penetration energy with the associated ridge cross sectional area, the minimum size of ridge where the ship must resort to ramming can be determined. Ridge testing is normally performed in large ridge fields in order to establish the capability of the icebreaker in the most onerous conditions. By interpolating between the performances in level ice and in the large ridge fields, the performance can be determined in intermediate and small ridges.

The calculations for the resistances, energies and ridge profiles for the Polar Star, Polarstern, Oden and Otso are given in Appendix C. The following subsections discuss the results and compare them to the results obtained in phase 1.

8.2.2 Data Analysis

As discussed in the background references the ridge resistance can be considered as consisting of two parts; the resistance in the consolidated layer and the resistance in the above and below water rubble. The total resistance is the sum of the two. It is calculated by summing the net thrust form the propulsion system and the mass force determined from the deceleration of the ship, including a factor of 30% [91] for the added mass of the ship. The resistance in the consolidated layer is calculated from the level ice performance data. It was calculated for the speed in each segment of a ram if the speed data were available or for half the impact speed assuming a constant deceleration. The penetration energy was calculated from the resistances and the associated penetration distances and summed for the total penetration distance. The resistance in the consolidated layer used in the plots in this section were based on the average of half the impact speeds for all the rams.

The ridge cross sectional areas were calculated from the drawings of the ridge profiles. For the largest ridge in the Polarstern trials, the boring equipment was only able to reach

a maximum depth of 11 m. As a good above water profile was available the below water profile was calculated by a methodology based on equilibrium of above and below water masses [83]. This profile was combined with the known below water profile to provide an estimate of the cross sectional area. The Oden profiles were obtained in a similar manner from stereoscopic photographs of the above water relief. The thickness of the consolidated layer was taken as 1.5 times the level ice thickness for the Polarstern and Otso (1.5 m and 0.90 m respectively). For the Polar Star, it was assumed to be the thickness calculated from the initial resistance (per the methodology adopted in [38]). The values for the two rams were averaged for the plot (0.99 m). The consolidated thickness for the Oden was assumed to be the level ice thickness or 0.69 m. The effective average thickness used in the plot of resistance versus thickness was calculated for each ship from considerations of the ridge profile and the bow length and is explained in Appendix C. Ice properties were not available for the ridges, all of which were first year. The following data does help to categorize the ice:

Ship	Temperature (Air)	Water Type
Polar Star	0 to -4 (April)	Salt
Polarstern	-5 to +5 (May/June)	Salt
Oden	+1 (March)	Brackish
Otso	N/A (March)	Brackish

With the exception of three of the four Polarstern rams and one of the Oden rams, all of the ships penetrated the ridges completely. In most cases however, the speed data only extended to the point where the stem at the waterline just cleared the ridge. The analysis of resistances and energies should extend to the point where the widest part of the ship (i.e. the end of the bow) just clears the end of the ridge. This was only possible for the Polar Star rams.

The average ridge resistance including the consolidated layer is shown in figure 8.1, plotted against the effective average ridge thickness. The comparable results for the Kigoriak and the Robert Lemeur from Phase 1 have been included for comparison. It should be noted when examining the results that the ships all have different midship areas and hence create different size holes. The midship areas for the drafts used during the tests are shown in table 8.1 in ascending order.

Clearly with the differences in midship areas, consolidated layer thicknesses and impact speeds definitive comparisons are not possible without further analysis. Trends are however evident. Allowing for the differences in consolidation resistance and thickness, the resistance of the ships are generally arranged such that increasing resistance occurs with increasing midship area. The exception is the Oden which does not have the highest resistance despite having the highest midship area. This is shown in table 8.1, column 4, where the

resistances are divided by the Kigoriak's resistance. When compared with the midship areas divided by the Kigoriak's midship area (table 8.1, column 3), it can be seen that some of the other factors such as environmental and ice conditions, and hull shape influence the results.

Figure 8.2 plots the energy required to penetrate a given cross sectional area of rubble. Only the Robert Lemeur, Kigoriak and the Polar Star are in the correct sequence based on their midship areas. The energy to penetrate a given area for each ship has been divided by the energy required by the Kigoriak for the same area (table 8.1, column 5). These ratios when compared to the midship area ratios, show that the three ships mentioned above are close to the values expected based on considerations of area alone. The values for the other ships are influenced by other factors as mentioned in the preceding paragraph.

Figure 8.3 combines the data used in the preceding figures but scales the values for the resistance to the midship area of the Kigoriak. The plots for the ships seem to fall into 3 distinct groups: the Robert Lemeur and the Oden, the Kigoriak and the Otso and the Polar Star and the Polarstern. Table 8.2 compares the resistances of each ship divided by the resistance of the Kigoriak with the average buttock and flare angles again divided by the angles of the Kigoriak. For the buttock angles only the Robert Lemeur and the Otso show similar trends for buttock angle and resistance, i.e. decreasing resistance with decreasing buttock angle. For the flare angles, only the Otso shows a reverse trend to that seen in level ice, i.e. the resistance decreases with increasing flare angle. The Oden and the Robert Lemeur have the highest flare angle (66.4 and 72.5 degrees respectively) although the environmental conditions for each series of rams were quite different. (The trials of the Kigoriak and Robert Lemeur were conducted in saline water with air temperatures colder than -20 degrees C). The flare angles for the Kigoriak and the Otso differ significantly (58.5 and 42.8 degrees respectively) but the environmental conditions differ in the same manner as the Robert Lemeur and the Oden. This would suggest that the more favourable environmental conditions have offset the less favourable flare angles. The average flare angles of the Polar Star and the Polarstern are similar although the resistances differ.

8.3 Ramming Cycle Performance

8.3.1 General

As mentioned in the introduction to this section the data consists of two sets; one set for level ice ramming for the Arctic (old bow) and Louis S. St. Laurent and the other for ridge and rubble ramming for the Franklin. The Franklin data may contain some level ice rams but it is not clear from the environmental data. The available data are summarized in table

8.3 which contains the averages for each ram set. The data from which these averages were derived are found in Appendix C.

With the exception of the Arctic's ram set in thick ice (Jul 81-1), the ice was weak in the level ice trials. In general the ice at this time had undergone significant surface melting leaving puddles of water and no snow. Temperatures were at or above freezing. In the St. Laurent trials, the ice was described as heavily puddled and decayed with thaw holes appearing at the end of the test period. These conditions imply low friction and very weak ice. The Franklin ridge and rubble trials were conducted in temperatures ranging from -28 to -16 degrees C and with snow covers averaging from 25 to 60 cm. The average level ice thickness was 95 cm in the region of the trials. These conditions imply high friction.

The trials of the Arctic and the St. Laurent were conducted in saline water in Admiralty Inlet and Strathcona Sound, whereas the trials of the Franklin were conducted in Lake Melville in brackish water.

8.3.2 Data Analysis

The Franklin rams were divided into two sets by selecting those rams with penetration distances equal to or less than 30 m (set 82-1) and those greater than 30 m (set 82-2). (See Appendix C for details.) Rams with penetration distances greater than 30 m were judged to be too close to continuous ahead performance. Despite similar backing times and acceleration times and distances, the penetration distances and times differ by factors of about five times. As snow thicknesses were similar in both sets the differences can be attributed to the increased average ice thickness in the first ram set. The average ice thickness of 1.15 m in the second ram set is close to the average level ice thickness in the area of the trials (0.95 m) and hence this ram set is similar to those in part A of table 8.3 (i.e. level ice ramming). The Franklin had recently been painted with Inerta and unlike the rams in 1981 in Lake Melville, rarely became stuck.

The 1981 Arctic rams were divided into three sets [4]. The first set was in thicker ice which consisted of a completely refrozen ridged area with gradually varying thicknesses. The other two sets were in level ice. The rams in set 1 were at level keel with the bubbler on or off. The rams in set 2 were all with level keel and the bubbler on. The rams in set 3 were with the bow up and the bubbler either on or off. Details are given for each ram in Appendix C.

In sets 1 and 2 in 1981 the backing and acceleration times are similar. Because of the thicker ice in ram set 1, the Arctic is not able to back as far nor is she able to achieve as great an impact speed. This thicker ice and reduced impact speeds result in penetration distances five times less and extraction times five times more.

In ram set 3 and the June 1982 ram set, the ice conditions and ram cycle times are similar but the penetration distances are in the 1982 set are 62 % larger. The 1982 tests used a standard backing distance of 0.5L, which compares with the 0.41L used in the 81-3 set.

Ram set 81-2 for the Arctic and the ram set for the St. Laurent have similar ice thicknesses and impact speeds. The kinetic energy for the Arctic is 3.4 times that of the St. Laurent and the Arctic's beam is 94 % of the St. Laurent's, yet the penetration distances for the Arctic are only 90 % of the St. Laurent's. As the bow angles on the Arctic are more favourable than on the St. Laurent, clearly the ice on the St. Laurent trials was very weak and provided little resistance.

8.4 Conclusions

The conclusions are divided into those for the ridge ramming resistances and energies and the ram cycle times.

Ridge Resistance and Penetration Energy

- the energy and resistance for penetrating a given ridge profile are primarily dependent upon the largest cross sectional area of a ship

- the higher the average bow flare angle the lower the resistance and energy required to penetrate a given ridge profile. Buttock angle shows no similar trend for the limited range of data examined.

- as environmental conditions (air temperatures and ice condition) also influence the resistances and energies, they should be carefully documented during full scale trials

Ram Cycle Times

- in level ice impact speeds are dependent on the ice thickness

- in level ice, extraction times increase with increasing ice thickness

- for a given ship backing and acceleration times tend to be independent of the environmental conditions. The backing distances to achieve these times are determined by the master. Penetration times increase dramatically as the ice thickness approaches the level ice thickness in which the ship can operate continuously.

- the ice properties and environmental conditions play a major role in the performance and must be well docu-

nested

- the lower the power/displacement ratio, the longer the ram cycle time for equal conditions

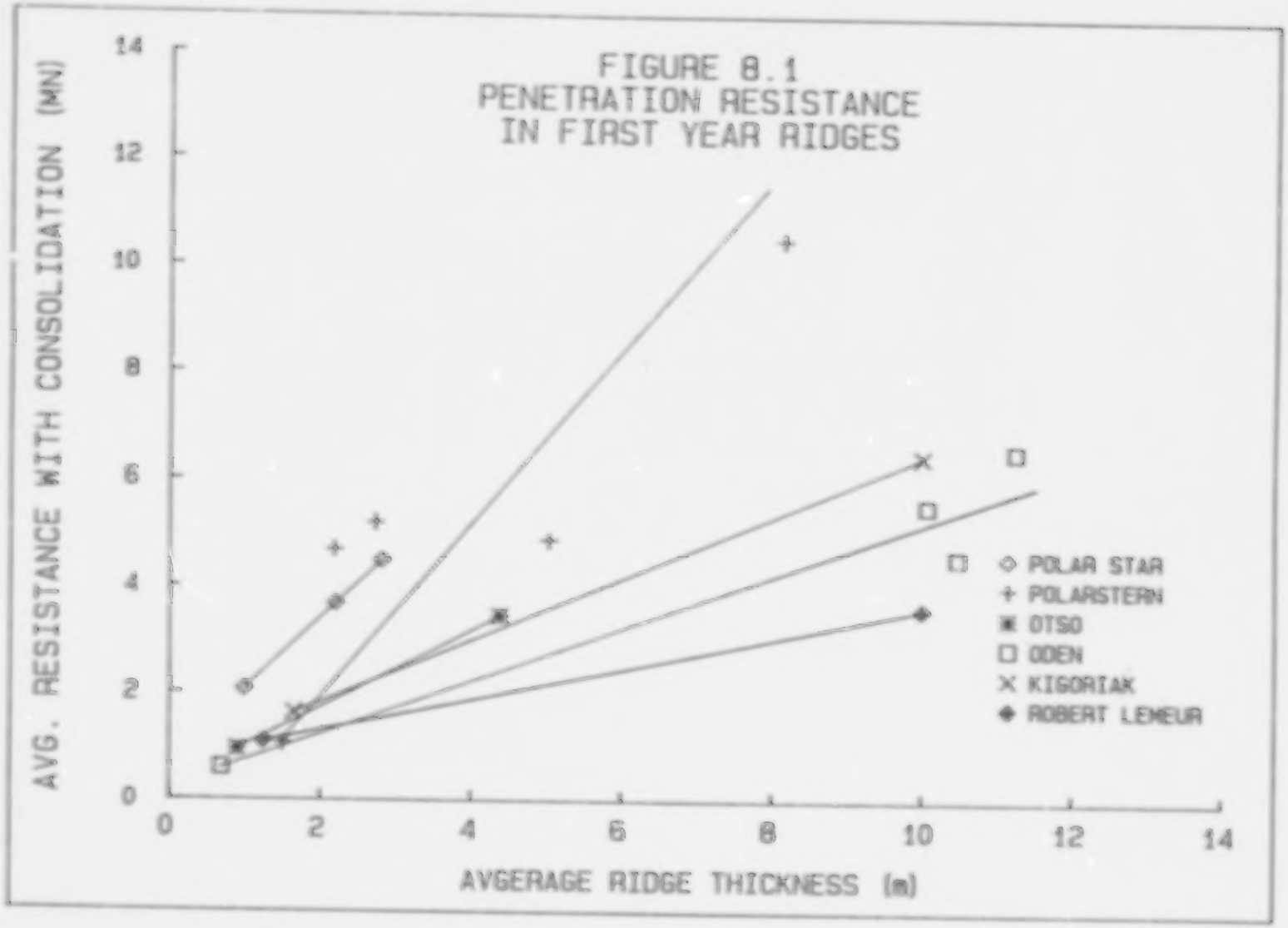


FIGURE 8.1
PENETRATION RESISTANCE
IN FIRST YEAR RIDGES
AVG. RESISTANCE WITH CONSOLIDATION (MN)
AVGERAGE RIDGE THICKNESS (m)
0
2
4
6
8
10
12
14
POLAR STAR
POLARSTERN
OTSO
ODEN
KIGORIAK
ROBERT LEMEUR

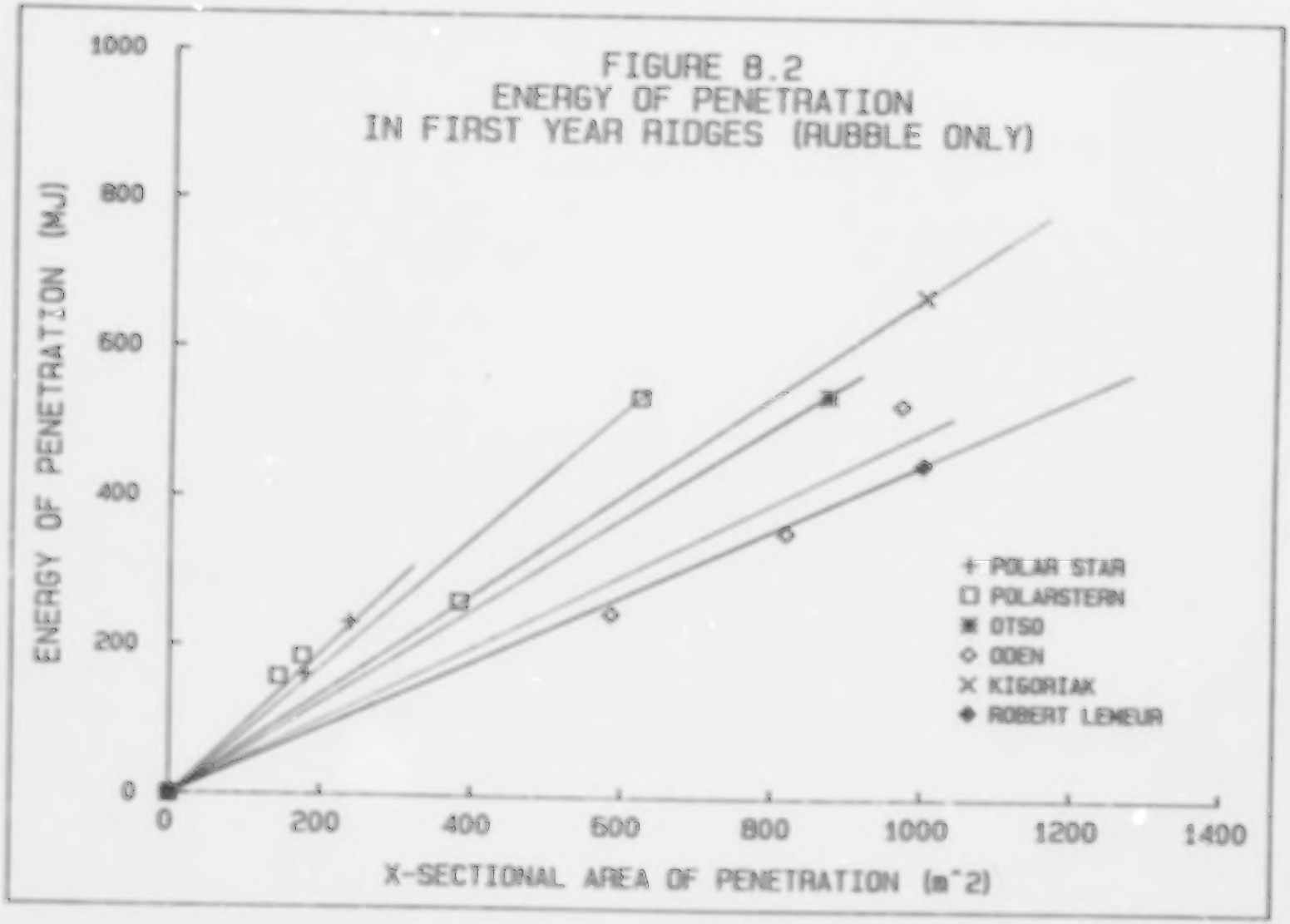


FIGURE 8.2
ENERGY OF PENETRATION
IN FIRST YEAR RIDGES (RUBBLE ONLY)
ENERGY OF PENETRATION (MJ)
1000
800
600
400
200
0
0
200
400
600
800
1000
1200
1400
X-SECTIONAL AREA OF PENETRATION (m^2)
POLAR STAR
POLARSTERN
OTSO
ODEN
KIGORIAK
ROBERT LEMEUR

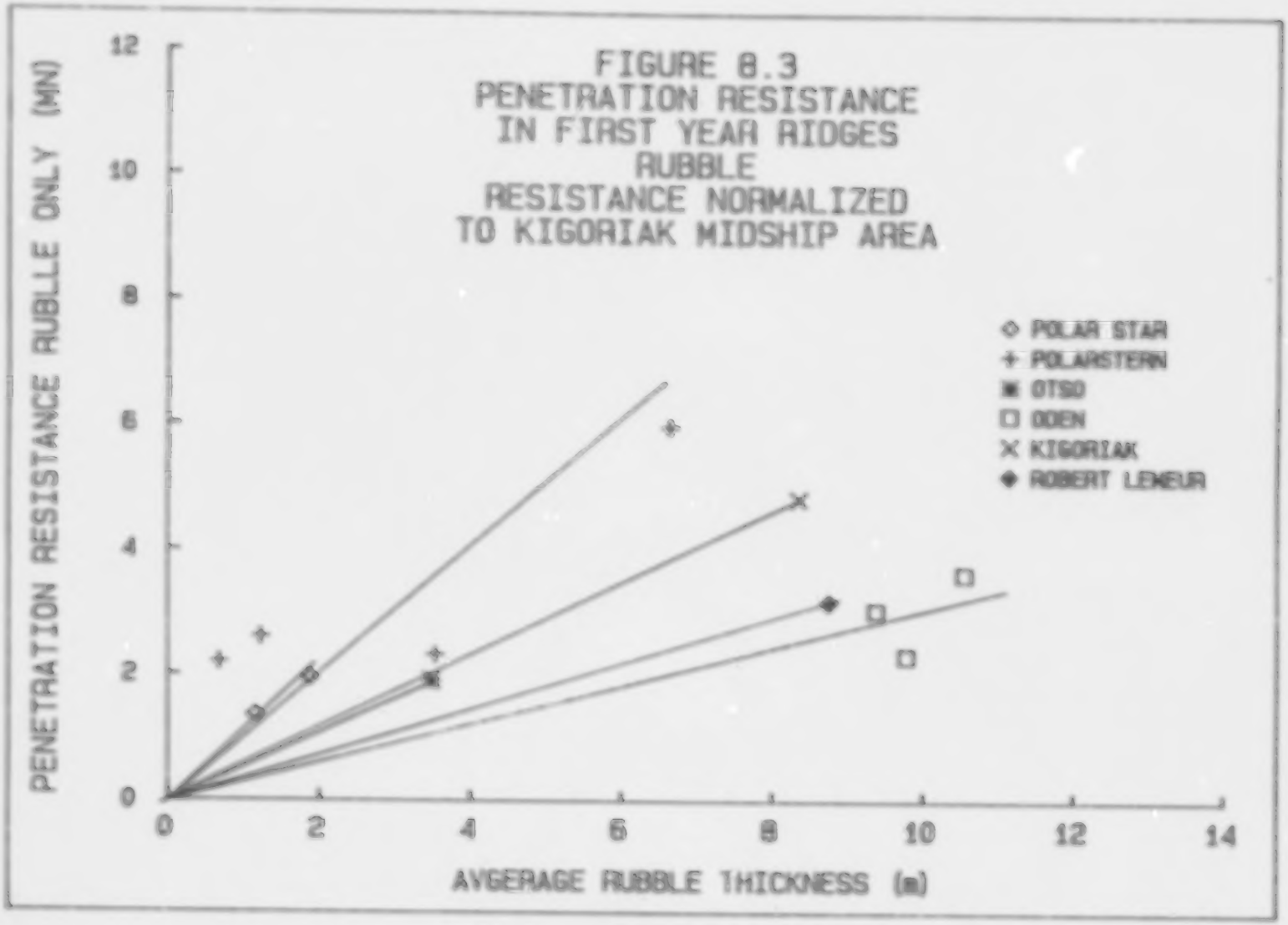


FIGURE 8.3
PENETRATION RESISTANCE
IN FIRST YEAR RIDGES
RUBBLE
RESISTANCE NORMALIZED
TO KIGORIAK MIDSHIP AREA
PENETRATION RESISTANCE RUBLLE ONLY (MN)
AVGERAGE RUBBLE THICKNESS (m)
POLAR STAR
POLARSTERN
OTSO
ODEN
KIGORIAK
ROBERT LEMEUR
0
2
4
6
8
10
12
14

TABLE 8.1

ENERGY AND RESISTANCE VERSUS HIGHUP AREA

SHIP	HIGHUP AREA 40/60(KIN) FIG. 8.1 RES/MEX(KIN)		FIG. 8.2 EN/DE(KIN)	
	M^2			
ROBERT LEMEUR	101.9	0.79	0.45	0.42
EDWARDIAN	129.7	1.00	1.00	1.00
OPTIM	142.3	1.25	1.25	0.92
POLAR STAR	165.4	1.28	2.21	1.40
POLARSTERN	208.4	1.59	2.75	1.26
KNOX	266.2	1.39	0.85	0.72

TABLE 9.2

RUBBLE RESISTANCE AND BOTTOCK AND FLARE ANGLES

SHIP	RESISTANCE RES/RES(KIS) AT BOT ANG ABA/ABA(KIS) AT FLR ANG AFA(KIS)/AFA					
	NO		DES		DES	
ROBERT LEMEUR	1.66	0.63	17.8	0.74	72.5	0.81
KINGSMAN	2.31	1.00	24.1	1.00	58.5	1.00
OTSO	2.23	0.96	21.1	0.88	42.8	1.37
POLAR STAR	4.34	1.88	22.0	0.87	45.2	1.29
POLARSTERN	3.79	1.64	23.8	0.95	49.0	1.30
ODEN	1.33	0.58	28.7	1.02	66.4	0.88

TABLE 0.3

RAM CYCLE TIMES

PART A

LEVEL ICE RAMMING RAM CYCLE TIMES AND RAM DATA

SHIP	RAM SET	ICE THK. FLEX.	SHOCK IMPACT VEL.	DIST. PEN.	DIST. ACCEL.	TOTAL CYCLE	BACKING	ACCELER.	PENETRATION	EXTRACTION
		ft	ft/s	ft	ft	sec	sec	sec	sec	sec
ARCTIC	JUL 81-1	2.55	362	4.37	22	126	519	292	134	29	63
	JUL 81-2	1.57	(15)	5.36	124	160	524	262	130	126	16
	JUL 81-3	1.62	(15)	4.02	85	92	401	180	73	115	30
ARCTIC	JUNE 1982	1.40	(15)	4.07	139		383				
ST LAURENT	JULY 1979	1.64	(15)	5.13	135		327				

PART B

ICEAE AND RUBBLE RAMMING RAM CYCLE TIMES AND RAM DATA

SHIP	RAM SET	ICE THK.	SNOW THK	IMPACT VEL.	DIST. PEN.	DIST. ACCEL.	TOTAL CYCLE	BACKING	ACCELER.	PENETRATION	EXTRACTION
		ft	ft	ft/s	ft	ft	sec	sec	sec	sec	sec
FRANKLIN	RAM 82-1	1.30	0.46		20	80	239	65	80	55	0
	RAM 82-2	1.15	0.45		103	69	432	84	74	293	0

NOTE: 82-1 ICEAE RAMS WITH PENETRATION DISTANCES OF LESS THAN 30 ft
82-2 ICEAE RAMS WITH PENETRATION DISTANCES GREATER THAN 30 ft

9. TRANSIT

9.1 Introduction

A transit is a voyage from point A to point B in a regime of mixed ice conditions. The performance of the ship is assessed by the average speed over the distance covered.

The ice regime will include:

- level ice
- ridges
- rubble fields
- pack ice in varying concentrations
- open water (including leads)

If significant wind or currents are present the ice may be pressured.

To fully define the transit, ice properties and environmental conditions should be measured. These include:

- thicknesses of level ice, ridges etc.
- snow cover
- ice strength
- frequency of ridging
- extent of ice type (distance that ship travels)
- temperatures, wind speeds and directions
- floe size and ice concentration
- ice type and concentration

The ship power and speed in each of the ice conditions should be measured as well as an assessment of the hull condition.

In the present data set, the following transit information exists:

Sir John Franklin

- five probes into Lake Melville in 1980 (January and March), 1982 (January and March) and in 1983 (April) [10]

- transits through the pack ice off the entrance to Lake Melville in March 1980 and April 1983 [10]

M.V. Arctic

- transit to Bent Horn through a mixed regime including multi-year ice [29]

The environmental data associated with these transits is not directly comparable because of the different levels of

effort in collecting the data and the different criteria in categorizing the data. Direct comparison of the results should not be made, although the general trends can be compared.

Other transit data exists for the USCG Polar Star and Polar Sea and the Arctic, but the results have not been analysed in a form suitable for comparison between ships and ice conditions.

9.2 Analysis of Results

The available data for the Franklin inbound transits within Lake Melville are shown in table 9.1. In bound transits have been selected as they were through unbroken ice and tended to follow the easiest available route. Outbound transits tended to follow the inbound broken track.

The lack of any ramming data for individual ridges and data for the ridges themselves, makes a detailed comparison between the probes impossible. General observations can however be made.

The coating of the hull with Inerta has made a large difference in the performance in ridges and rubble fields. The March 1980 and 1982 voyages were in similar conditions i.e., thick first year ice with a deep snow cover and ridging. In the 1980 transit the extraction process for ahead rams became so difficult that the ship was taken through the ridges stern first. The lubrication of the ice by the wash from the propellers enabled slow progress. In the 1982 transit, the ship did not become stuck and all ramming was performed ahead. The increase in average trip velocity is significant (1.17 knots to 1.94 knots).

The lack of snow in the April 1983 transit has almost doubled the average velocity over that achieved in the March 1982 transit in ice of similar thickness, but with snow. This must be treated with some caution as the extent of ridging is not known.

The thin ice and no snow cover in the January 1982 transit ensures high level ice speeds. When ramming ridges, the impact velocities are high and hence the available kinetic energy is large allowing the ship to penetrate most ridges in the first pass. Despite the relatively high level ice speed in the January 1980 transit, the ratio of actual trip velocity to the level ice velocity is much lower than the January 1982 transit due to the tendency to stick in the ridges and the increased number of rams required because of the greater maximum ridge thickness.

The transits in pack ice of the Arctic and the Franklin are plotted in figure 9.1, based on the data in table 9.2. The

speeds have been expressed as a percentage of the maximum open water speed achievable by each ship. The average ice concentration has been expressed in tenths. The major difference between the two data sets is the presence of significant quantities of multi-year ice on the Arctic transits.

Up to ice concentrations of 7.5 to 8.5 tenths, both ships are able to maintain relatively high speeds; the Franklin about 90% of her maximum open water speed and the Arctic about 80%. The Franklin's speed has been set in some measure by the choice of 4 of 6 main engines to achieve an economical speed. Due to the greater manoeuvrability of the Franklin, it would be expected that she could maintain a higher speed than the Arctic and still avoid the ice floes.

Above ice concentrations of 7.5 to 8.5 tenths the speed of the Arctic is reduced very quickly to approximately 20% of her open water speed at 10 tenths coverage. As seen from the ice regime data in Table 9.2, the transit segments where the power and hence speed have been reduced are generally associated with high concentrations of old ice and medium to vast floes. The reduction in power is linked to the increased risk of damage from high operating speeds in old ice contained in large floes as the ship has limited capability to manoeuvre around the floes. In the high power voyage segments, the ship was operating in heavy concentrations of old fractured ice. The high powers were required to maintain progress in the thick ice, but the small size of the ice pieces posed a lower risk of damage.

The data for the Franklin appears to give two distinct operating procedures in high ice concentrations. In ice thicknesses up to 1.1 m and in smaller floe sizes, the ship is able to maintain high average speeds (above 60% of open water maximum). The operator is clearly not concerned about the risk of damage as he is operating in first year ice of limited thickness. In ice thicknesses of 1.3 to 1.4 m and in large floes (greater than 1500 m) the speed is reduced to less than 40% of the open water maximum. In pressured ice this speed is further reduced to 13%. The ship is not able to push the large floes aside and to manoeuvre around them would be too time consuming. She must therefore break some of them reducing the average speed. As the ship is not able to break continuous level ice of these thicknesses, the ability to maintain relatively high speeds demonstrates the reduced resistance in a discontinuous nonhomogeneous ice field.

9.3 Conclusions

1) The ability to operate efficiently in ridges (i.e. minimum extraction times) will determine the effective average transit speed in heavily ridged conditions. The risk of getting stuck is greatly reduced by the addition of inserts and increased by the presence of thick snow cover.

2) The average transit speed can be expressed as a percentage of the level ice speed. It is clearly a function of the time spent in ramming which in turn is a function of the ridge frequency and severity. To properly assess a transit, ridge data must be known.

3) For effective transit in ridged conditions, the speed in the level ice to be encountered should be well in excess of minimum requirements. This will ensure a reserve for the ridges for high impact speeds and hence effective penetration per ram.

4) For ships with limited strength, operation in high concentrations of old ice with large floes will bring about a voluntary speed reduction to minimize the risk of damage. The limiting speeds in first year ice conditions are set by the performance capability of the vessel, damage not being a major concern.

5) Pressure can cause a significant reduction in the average speed.

6) In pack ice conditions, the vessel is able to maintain progress at relatively high speeds in large floes of thicknesses greater than her continuous level icebreaking capability. In level ice of these thicknesses the ship would be continuously ramming resulting in very low average speeds.

7) In high ice concentrations in both first year and old ice, the size of the floe is a major determinant in the transit speed attainable.

8) In ice concentrations up to about 8 tenths coverage, vessels are able to maintain average speeds in excess of 75% of their maximum open water speed as they are able to manoeuvre around the ice. The presence of old ice, the manoeuvrability of the vessel and economical power levels are factors in determining the actual speed.

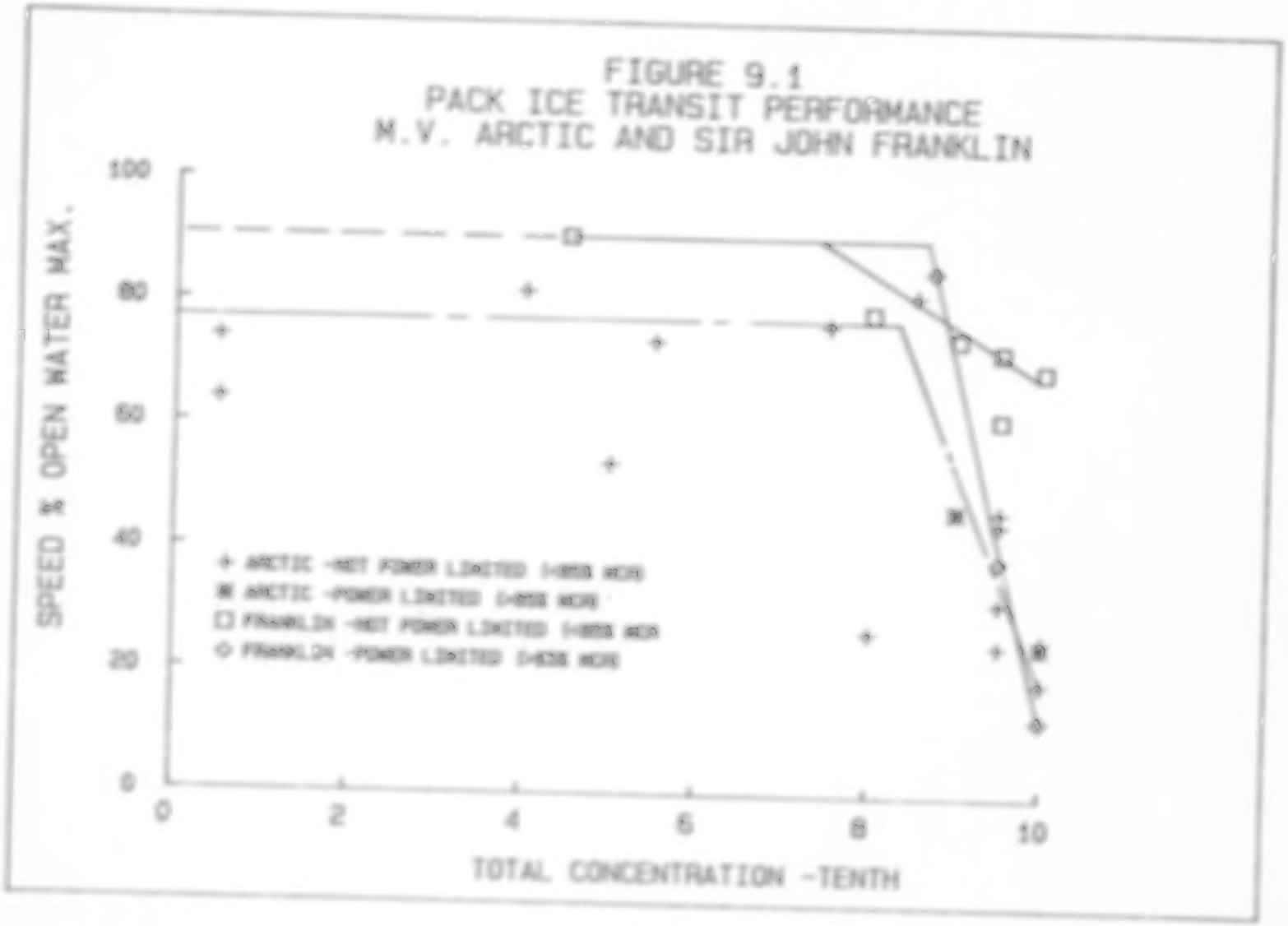


FIGURE 9.1
PACK ICE TRANSIT PERFORMANCE
M.V. ARCTIC AND SIR JOHN FRANKLIN
SPEED % OPEN WATER MAX.
100
80
60
40
20
0
0
2
4
6
8
10
TOTAL CONCENTRATION -TENTH
ARCTIC -NET POWER LIMITED (-6858 HCR)
ARCTIC -POWER LIMITED (-6858 HCR)
FRANKLIN -NET POWER LIMITED (-6858 HCR)
FRANKLIN -POWER LIMITED (-6858 HCR)

[illegible]

[illegible]

	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	57	48	39	39	43
[illegible]	11.5	12.3	2	9.3	11.8
[illegible]	0.4	0.79-0.89	0.4	0.91-1.09	0.91-1.1
[illegible]	0.89-0.15	0.3-0.3	0	0.3-0.7	0
[illegible]	1 (NM)	1.3 (NSW)	0.33-0.33	NS	3.4 (NM)
[illegible]	NA	NA	NA	NA	NA
[illegible]	0.43	0.25	24	NS	0.25
[illegible]	NS [illegible]	NS [illegible]	[illegible]	[illegible]	[illegible]

[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
		[illegible]		[illegible]	[illegible]

[illegible]

[illegible]	0.49	3.55	11.59	3.59	4.59
[illegible]	4.76	1.27	16.59	1.76	3.44
[illegible]	0.42	0.33	0.75	0.35	0.45

TABLE 9.2

PERFORMANCE OF PASS CCC: ARCTIC AND PEARLIN

SHIP	DAY	CC CONC. TONNES	OLD ICE TONNES	FY ICE TONNES	ICE THK M	FLOE LGTH M	PRESS KN	V KNS	POS. DIST.	V AND RA COMMENTS
PEARLIN AND RA		9.0		9.0	1	15		17	12.40	75
LAKE HOLMVILLE		9.3		9.3	0.9	20		17	12.80	73
		10.0		10.0	1.1	10		17	13.40	70
		9.5		9.5	1.1	15		17	15.20	62
		10.0		10.0	1.4	150		105	7.10	13 PRESSURE
		9.3		9.3	1.3	200		100	4.40	19 NO PRESS.
	445 63	4.3		4.3	0.3	500-600		17	15.00	95
		8.7		8.7	0.8	20-200		85	14.30	80
		8.0		8.0	0.4	20-100		17	13.00	75
ARCTIC	445 67 30	1.0	9.0		90	90	9.4	05	0.00	47
EDDY KING		10.0	9.0		90	90	9.3	05	4.20	20
	445 67 60	9.5	9.5		90	5000	7.6	07	7.70	45
		5000		5000	90	2000	8.2	79	10.10	60
	537 67 30	9.5	8.0	2	90	10-400	5.4	07	4.20	25
		8.0	3.0	5	90	400	3.7	30	4.60	27
		9.5	4.0	5	90	400	4.4	40	5.20	47
		7.5	7.0	5000	90	800	7.0	75	13.30	77
		4.0	1.0	4	90	800	8.2	75	14.20	82
		10.0	8.0	2	90	4000	4.9	07	5.20	29
	537 67 60	10.0	8.0	2	90	5000	8.0	73	4.40	26
		5.5	1.0	4.5	90	2000	8.0	73	12.80	74
		6500		5	90	40	8.1	74	12.80	74
		8.5	2.0		90	1000 400	7.0	66	14.20	82
		5.0	4.0	1	90	1000 800	6.2	56	9.80	56
		9.0	4.0	3	90	800-4000	4.9	60	5.30	30

10 PROPELLER/ICE INTERACTION

10.1 Introduction

The available data for propeller/ice interaction for the ships in this study are given in table 10.1. The thrust and torque interactions have been measured in terms of the percentage of open water maximum continuous thrust and torque. Values are recorded for both ahead and astern in various ice conditions while performing different manoeuvres. No information has been given on the type of interaction i.e., single impact, multiple impact or blockage for the nozzled ships. Nor is there any information on the duration of the event. Other than for the Arctic with the old bow there is no information on the frequency of the events. The data is therefore not comparable to that presented in the phase 1 study [91].

10.2 Data Analysis

For the Arctic the highest loadings occur during manoeuvring, when the propeller is most exposed to ice ingestion as the stern swings over towards the ice edge. The other high loadings occur at higher speeds in broken channels when the ice, broken and submerged at the bow, doesn't have as much time to rise to the surface before reaching the plane of the propeller. Generally low speeds and powers are used astern and hence the loads are not as high as ahead despite the increased risk of interaction. In general the loadings with old and new bows appear to be similar. However with the thrust signal reaching a saturation peak, the maximum values with the old bow are not available. The loadings for the old bow are infrequent, suggesting that the deep immersion of the propeller, the length of the ship and the presence of the nozzle all contribute to minimum ice interaction.

The highest loadings on the Radisson occur astern in a mixed regime of ice with a high concentration (7 tenths) of multi-year ice. This confirms the results of the interview, as the master exercises great care when backing with multi-year ice present. The thrust loadings on the open screw of the Radisson are 22% higher than the loadings on the nozzled propeller of the Arctic.

The Ann Harvey (an 1100 class), operating in relatively thin first year ice (0.53 m), has reached loadings comparable to the Radisson operating in far more severe conditions. As learned from the interview of the Martha Black's captain, the highest loadings occur astern as the propellers are very exposed. The next highest loading occurs ahead during channel breakout when the stern swings into the ice exposing the outboard propeller to unbroken ice. Again, this confirms the concern of the master about the high risk of propeller damage while manoeuvring. The high loadings in moderate ice conditions

explain the high blade breakage rate (5 times in two years) when the Martha Black is operating in multi-year ice in the Western Arctic.

The data for the Samuel Risley (a 1050 class), are very limited and it is thought that they are ahead values. It is also assumed that at the lower speeds, lower power levels have been used. The results are clearly lower than the Ann Harvey in thicker ice, suggesting that the nozzles and hull form give lower loadings than open propellers.

The testing associated with the Oden value is considered to be very severe i.e., ramming astern into a ridge composed of first year ice. The number is comparable to the values of the Radisson and Ann Harvey operating in level first year ice. Comparison of the values suggests that the nozzles of the Oden are effective in minimizing propeller loads.

10.3 Conclusions

1) The highest loadings occur during backing and manoeuvring.

2) Increasing speed in channels will increase the propeller loading due to increased impact speeds and the increased amount of propeller/ice interaction as the ice does not have as much time to float clear of the plane of the propeller.

3) To enable valid comparisons between ships, the following values should be recorded:

- torque and thrust levels as well as the actual power level
- the environmental conditions (ice thickness, type, strength etc.)
- the type of manoeuvre
- frequency of occurrence with the associated threshold values

TABLE 10.1

PROPELLER/ICE INTERACTION

SHIP	ICE CONDITIONS	T % MCR	Q % MCR	FREQUENCY	COMMENTS
ARCTIC (NEW)	LEVEL ICE MAX THK = 1.55 M	134-AH			HIGH POWERED RUNS
	BROKEN CHANNEL THK MAX = 1.83 M.	150-AS			V (3 KTS
		170-AH			HIGH V
	MANOEUVRING - ADMIRALTY INLET	155-AH			STEADY STATE TURNING
		198-AH			CHANNEL BREAKOUT
		170-AS			CHANNEL BREAKOUT
	RAMMING - PRIMARILY LEVEL ICE	160-AH			EVENTS EVEN NO. AS/AH
		128-AS			
ARCTIC (OLD)	LEVEL ICE THK 0.2 TO 0.3 M				NO INTERACTION
	MIX ICE: LI 0.2 TO 0.6, 2+ MY 2-4 M	129-AH	141-AH	14 IN 9.6 HRS	
	BROKEN CHANNEL: FY THK 1.5 TO 1.8	134-AH	121-AH	11 IN 10.3 HRS	
	RAMMING LI THK 1.5 TO 1.8 M	133-AH	149-AH	44 IN 36.5 HRS	THRUST REACHED SIGNAL SATURATION
	RIDGE RAMMING FY IN LEVEL ICE				NO EVENTS EXCEED MCR VALUES
ODEN	RIDGE RAMMING ASTERN FY ICE		144-AS		
RADISSON	TRANSIT/RAM	188-AH	192		
	9/10 COVER 7/10 MY 2.3 TO 3.4 M	241-AS			
	LEVEL ICE FY DETERIORATING	150	150		
	TURNING LI FY DETERIORATING				OUTBOARD SCREW MEAN Q 36%) MCR
					INBOARD SCREW MEAN Q 23%) MCR
ANN HARVEY	OPEN WATER		120		
	FY ICE THK = 0.53 M + 0.10 SNOW				
	LEVEL ICE		129-AH		
			158-AS		
	FRESH BROKEN CHANNEL		112-AH		
			186-AS		
	TURNING LI		139-AH		
	CHANNEL BREAKOUT		173-AH		
	STAR MANOEUVRE		202-AS		ASSUMED ASTERN
	ESCORT		150-AS		ASSUMED ASTERN
SAMUEL RISLEY	FY LEVEL: THK = 0.75 M + 0.05 SNOW	98	83		V (5 KTS
		106	117		V) 5 KTS

11. MATHEMATICAL MODELS

11.1. General

Mathematical models are developed here for estimation of performance of the ships for which there has been full scale data available in this project. The models are developed for level ice resistance, ridge penetration energy, turning circle size, and for open water resistance. The types of models developed are semi-empirical, closer to being empirical than physical theory based. The key consideration has been the validation of the models by use of the full scale data.

There were similar simpler mathematical models developed in (design synthesis I). In this project, there has been an extensive coverage of ship and environmental parameters. Consequently it has been possible to develop a more comprehensive model for the level ice and the ridge resistance.

The sections in this chapter covering the models are:

11.2. Level Ice Resistance
11.3. Ridge Penetration Energy
11.4. Turning Performance
11.5. Open Water Performance

Finally in Section 11.6. a summary is presented of all the models for application purposes. Also a discussion and definitions of the validity of the models and the coverage of parameters is included.

11.2. Level Ice Resistance

11.2.1. General

Level ice resistance analysis included the following steps.

- calculation of resistance from performance trials
- correction of resistance to a common ship size
- correction of resistance for hull condition
- correction of resistance to a common environmental base.
- analysis of the resulting corrected and normalized data for the influence of hull design features on resistance

11.2.2. Calculation of Resistance from Performance Trials.

Using the analyzed ship resistance from Section 4.5 in this report as basic data for model development the dependency of level ice resistance is arrived at.

The full set of data for level ice resistance at 1 m/s versus ice thickness, corrected to ship size, is shown in Figures 11.1A and 11.1B. Figure 11.1A contains data from current project, and Figure 11.1B from (design Synthesis I). The standard deviation around the regression line which is drawn for all the data (same in both Figures), is 23 percent.

The equivalent level ice thickness used as X-axis is the actual measured ice thickness plus one half of the snow thickness.

11.2.3. Correction of Resistance for Ship Size

All ship resistance data were first corrected to common dimensions of length, beam and draft. The dimensions of Kigoriak, waterline length 84.2 m, beam 19.25 m and draft 8.5 m were used.

For size correction, the dependency of resistance on size is used as follows:

$$R_{ice} = f\ (B^{0.7} * T^{0.1} * L^{0.2})$$

where

R_{ice} = ice resistance
B = maximum beam of vessel (m)
T = draft of vessel (m)
L = waterline length of vessel (m)

This correction reduced the scatter of data better than the simple traditional assumption that ice resistance is a linear function of beam. The formula was developed in the early eighties by Bengt Johansson of Canadian Marine Drilling.

11.2.4. Correction of Resistance for Hull Condition.

Ship resistance data were corrected to the common hull condition of a new Inerta coating, using data obtained from separate trials on Kigoriak in different hull conditions.

Kigoriak was tested in the bare steel condition, when 4 - 8 months old and again at approximately 3 years old, when there was a considerable degree of corrosion and a dramatic increase in resistance. Kigoriak was then coated with Inerta 160, and level ice trials were repeated. The results are found in [91]. The correction factor (C_h) derived for hull condition is shown in Figure 11.2. It is 1.0 for Inerta coating, 1.33 for 4 months old bare steel and 1.9 for 2 year old bare steel.

The hull conditions of all but one vessel were either bare steel or Inerta. It should be noted that no data were available on deterioration of Inerta with time, which is known to happen. The assumption has been made that such deterioration has no

effect on performance. This is considered reasonable since all trials were carried out no earlier than about 3 months after application of Inerta, but latest within two years following Inerta coating. Moreover, no allowance was for the known difficulty that some new Inerta applications begin to peel shortly after entering ice, since detailed information on hull condition at the time of the trials was rarely available.

One of the vessels, OTSO, has a 2 meter belt of stainless steel around its waterline, with Inerta above and below. Although it is recognized that the smoothness of stainless steel is even better than that of an Inerta coating, there are no published data on how much this might reduce ice resistance. Thus this particular set of data need to be treated with some caution in this respect. The data are used without correction as if the vessel had a complete Inerta coating.

11.2.5. Correction of Resistance to a Common Environmental Base.

Temperature/friction correction

The first correction introduced is an ice surface temperature correction, which is in fact a friction correction. It is known from studies with the Kigoriak, that the ice/hull friction coefficient varies with temperature [86]. Figure 11.3 shows the influence of temperature on friction coefficient for various hull ice/snow contact conditions as well as an average influence of temperature on friction coefficient. The friction tests covered dry and wet ice and snow as well as Inerta coating and bare steel hull. The field tests were performed at two temperatures of ~ 30° C and -10 °C, and similar laboratory tests at several temperatures. The laboratory friction tests confirmed the findings from the field tests regarding the friction and temperature dependency.

The correction to account for the influence of friction (through temperature) on ice resistance is arrived at in two stages. First, the influence of temperature on friction factor is taken as in Figure 11.3., and second, the influence of the change in friction factor upon ice resistance is assessed. This can readily be done based on model tests, or theoretically calculated resistances where friction is taken into account. Figure 11.4 shows the summarized influence of friction factor on resistance in level ice from model tests in level ice at the NRC Institute for Marine Dynamics, Newfoundland [88]. This applies best within the range of buttock angles from 20 - 25 degrees and flare angles from 45 - 60 degrees.

The final formula by which level ice resistance is corrected for friction to a common temperature of -15 °C, which was the average temperature during all full scale trials included, is:

$$C_t = 1 - 0.0083 * (t + 30)$$

where

C_t = friction temperature factor
t = ice surface/air temperature (^oC)

Ice Strength correction

The influence of ice flexural strength upon icegoing resistance was determined from well documented full scale trials data for Kigoriak and Terry Fox. The new aspect of this analysis is that the data are first corrected for the influence of temperature/friction, which occurs simultaneously with change in flexural strength. The remaining change in resistance now becomes the independent influence of flexural strength. Figure 11.5 presents the relative resistances of the Kigoriak and Terry Fox/Kalvik as a function of ice flexural strength. The dependency is close to identical for each vessel. The hulls were coated with Inerta and the resistance data are corrected to a common temperature/friction corresponding to -15 ^oC according to the above formula.

The resulting factor for correcting ice resistance to a common strength of 378 kPa which is the average flexural strength during all the trials is;

$$C_o = 0.63 + 0.00074 * \delta$$

where

C_o = Strength factor
δ = flexural strength of ice (kPa)

Water salinity correction

It was observed in an initial comparison of the resistance data on the basis of ice strength alone, that some data sets did not follow the expected trend of increasing resistance with increase in ice strength. In particular, level ice resistance in strong fresh water ice was surprisingly low. The same trend, although less marked, was observed for tests in brackish water ice. The simple explanation for this discrepancy is that ice formed of fresh water (or low salinity brackish water) is more brittle than ice of higher salinity. In practical terms, fresh, brittle ice of a given flexural strength and temperature consumes less energy in the breaking process than ice which has formed in saline water. The correction for this particular factor is currently based on a few sets of icebreaker tests, and mainly experimental data, and is shown in Figure 11.6.

A project is currently underway to determine the influence of several environmental parameters including salinity on the energy absorbed in the icebreaking process. This is expected to lead to improvements in the above correction factors.

11.2.6. Analysis of the Influence of Design Features on Level Ice Resistance.

The level ice resistance data, as corrected above to the common ship dimensions and hull and environmental conditions of length 84.2 m, beam 19.25 m , draft 8.5 m , Inerta coating, temperature -15 ^{o}C, flexural strength 378 kPa and saline water based ice, were analyzed for the influence of hull form parameters.

Hull form, as it influences icegoing resistance, is described in terms of the angles of the waterline bow shape. A two angle approach of average buttock and flare (or frame opening) angles over the full beam of the vessels is used. These angles have been found in the past to show good correlation with level ice resistance [91]. It should however be recognized that these angles will at best only account for ice breaking at the bow waterline. Moreover, being averages over the full beam, any important changes in bow shape from stem to the shoulder region will be masked.

As a consequence of the above, it was found that vessels with clear chines are handled more reliably using average angles than fully formed hulls. Chined vessels tend to have reasonably constant bow angles from the stem to the shoulders. Moreover, the sides of vessels aft of the chines tend to be vertical or close to vertical without introducing steep angles required to break ice. Fully formed icebreakers on the other hand tend to have at least a gradual change in bow angles across the full beam. In particular, flare angle will normally increase with increase in beam out to the shoulder region, sections thereafter becoming even steeper at the shoulder itself. It is expected due to this that a representation of the hull using average angles will be less accurate than for chined hulls.

In this presentation the vessels are divided into two groups, those with gradual shoulders (fully formed hulls) and those with sharp chined shoulders. One vessel, M.V.Arctic with its new bow is in between, having no sharp chines, but a shortened shoulder region which minimizes the interaction of unbroken ice and the hull in this shoulder region. For consistency M.V.Arctic is left in the rounded shoulder category.

For the chined vessels the bow form resistance dependencies are expressed:

$$C_{flare} = 1 + 0.0018 * (90-\psi)^{1.4}$$
$$C_{buttock} = 1 + 0.004 * (\varphi-5)^{1.5}$$

where
ψ = average flare angle over the bow (^{o})
φ = average buttock angle over the bow (^{o})

For rounded shape hulls similar dependencies are expressed:

$$C_{flare} = 1 + 0.0018 * (90-\psi)^{1.6}$$
$$C_{buttock} = 1 + 0.003 * (\varphi -5)^{1.5}$$

Summary of ice resistance after applying all corrections:

Ice resistance data for all vessels were corrected to the following common values for the environment and the ship:

B	= 19.25 m
L_{WL}	= 84.2 m
T	= 8.5 m
φ	= 25 degrees
ψ	= 50 degrees
σ	= 378 kPa
t	= - 15 ^{o}C
C_h	= C_s =1 (Inerta, Saline Water)

The resulting resistance formula for chined vessels is:

$$R_{ice} = 0.65 + 0.08 * H^{1.25} \quad (MN)$$

and for the rounded hull vessels

$$R_{ice} = 0.78 * H^{1.5}$$

The analysis reduces the scatter in the data for the chined vessels from the original 23 percent to 7 per cent standard deviation. The corrected results with a regression line is shown in Figure 11.7. For the round shouldered ships the reduction is from 23 per cent to 12 per cent. The corrected data and a respective regression line are shown in Figure 11.8.

Differences between these two groups are noted below.

- ice resistance increases with ice thickness at a greater rate for the rounded shouldered than for the chined ships. It is interpreted that the steeper angles in the shoulder regions induce more crushing than in similar regions in the chined hull family. The thickness exponent for crushing is 2, but for flexural failure it is closer to 1. Thus steeper angles at the shoulders increase the thickness exponent. The overall thickness exponent for ice resistance is 1.5 for rounded hulls and 1.25 for chined ones.

- There is considerably more scatter in the round shouldered as opposed to the chined ship data. It is interpreted, as explained above, that representation of the bow with average angles is much less accurate for round shouldered ships. This is expected to be the reason for the higher scatter.

The influence of flare angle and buttock angle on ice resistance are shown for chined ships and for rounded shouldered ships in Figure 11.9 for flare angle and in figure 11.10 for buttock angle.

The validity of these formulas is within the range of parameters of full scale data. There is no consistent range of the environmental or hull parameters, and because of this approximate range of parameters for which the formulas are considered reasonable are:

Ice thickness	0.5 - 1.7 m
Flexural strength of ice	150 - 700 kPa
Average flare angle	40 - 80 deg.
Average buttock angle	12 - 40 deg.

11.3. Ridge Penetration Energy

The ridge penetration energy model developed here is intended for the purpose of establishing a measurestick for the quality of a particular icebreaker hull in terms of amount of energy it is expected to consume in penetrating ice ridges. This evaluation can be compared varying the hull design and it can also used as input into ridge penetration models of the kind that are based on energy calculations.

Until the advent of these projects, the authors were not aware of enough publicly available ridge performance data, and in particular ridge penetration energy data in full scale, for an assessment of the influence of hull design on ridge penetration energies. The data available are from full scale trials on Kigoriak, Kontio, Oden, Robert Lemeur, Polar Sea, Polarstern. The analysis was rigorously performed using similar methodology for each of the ridge tests. This is based on [83,84,85].

Ridge resistance can be considered as consisting of two parts; resistance in the consolidated layer and resistance in the rubble above and below water level (unconsolidated layer). The ship's ridge resistance is the sum of the two parts. The total resistance at any point in the ram equates the sum of the net thrust from the propulsion system and the inertial force determined from the deceleration of the ship, including a factor of 1.3 for the added mass of the ship. The average resistance in the consolidated layer is calculated from the level ice performance data, at a speed corresponding to one half the impact speed. From the resistances and the penetration distances, the total penetration energy for a ram can be calculated. In thick ridges several rams may be required to penetrate the ridge fully. The total energy to penetrate the ridge is the sum of the energies for all the rams. The plotted data points are based on these total energies. The energy is plotted against the cross sectional area of penetration (rubble only), which is calculated from the ridge cross section for the total

length of penetration and the amount of consolidation assumed constant over the penetration length. Figure 8.2 shows the uncorrected data for the energy to penetrate the rubble portion of a ridge or a ridge field. In this figure, the scatter contains the influences of at least the following main parameters:

- hull shape and size
- ice properties
- hull condition

In ridge energy analysis there is expected to be more scatter than in level ice conditions, due to the fact that the ridges can not be defined as clearly and simply as level ice. Based on the data in Figure 8.2, it appears that the initial scatter is of the same order of magnitude as the initial level ice analysis; the standard deviation around the regression line being 26 %.

This data offers an opportunity to utilize similar correction factors as were used for the level ice resistance model. The correction for ship size was attempted in three different ways. By far the best ship size indicator for the ridge energy was the area of largest cross-section (others were beam and the size correction used for level ice resistance, containing beam, length and draft). The influence of temperature on friction and the influence of friction on resistance were adopted directly from the level ice corrections. The influence of strength which is indicated by the flexural strength, is not thought to influence the rubble energy in ridges as the ice is displaced rather than broken. However, displacing the rubble is expected to contain enough crushing of ice that the salinity index was adopted to describe this influence. The hull condition correction was also adopted from level ice resistance.

The influence of ship design can only be justified at the simplest level due to the very limited amount of data. Thus only one hull angle was used to explain the influence of hull design. By far the most important hull parameter to influence the resistance is the flare angle. It clearly makes a difference if the ship pushes the ice down into water rather than sideways into the adjacent rubble. Thus flat flare angles are considered to be very important for low ridge penetration energy.

The penetration energy for the rubble portion of the ridge was found to depend strongly on the largest cross sectional area of the ship. The bow geometry (mainly the flare angle) also influences the resistance. The environmental factors are similar to those for level ice. The rubble portion, ridge penetration energy is expressed by the formula:

$$E_R = 0.25*A_C*A_R*(1-0.0083*(t+30))*C_S*C_H*(1+0.012*(90-\psi))$$

Where

E_R = energy for ridge penetration (rubble only) (MJ)
A_C = largest cross-sectional area (m^2)
A_R = ridge depth * ridge profile length (rubble only) (m^2)
t = ice surface or air temperature (^oC)
C_S = water salinity correction
(saline = 1, brackish = 0.85, fresh = 0.75)
C_H = hull condition correction
(Inerta = 1, new bare steel = 1.33)
ψ = average flare angle for bow (^{o})

After these corrections the basic scatter in the data has been reduced to 10 percent. This is considered to be reasonable from such a limited set of data, representing a range of environmental conditions, different data collection techniques and quite different hull forms.

11.4. Turning Performance

11.4.1. General

The level ice turning circle data from ship full scale trials were first non-dimensionalised with respect to ship size and icebreaking capability. Figures C6.2.1 through C6.2.5 present the data. The Y-axis shows turning circle diameter non dimensionalized for ship size relative to waterline length. The X-axis presents the ice thickness in which individual turning tests were carried out relative to the icebreaking capability of the vessel at 1 m/s in similar ice at the same power level. This makes the data as independent as is possible of vessel power, hull and environmental conditions.

The non-dimensionalized data were analysed for the effect of design features on turning performance at a non-dimensional ice thickness of 0.6. This selection was made on the basis that it represents normal operating conditions for icebreakers and is in the middle of the range of ice thicknesses for the full scale trials.

Presentations of the turning circle data which were found to demonstrate the dominant influences of ship design parameters and features upon turning in a logical manner are given in Figures 11.12 for vessels with reamers and 11.13 for conventional vessels without reamers respectively.

11.4.2. Results for vessels with Reamers

Non-dimensional turning diameter is presented in Figure 11.12 versus reamer width per length of parallel side. This can be visualized as a direct measure of the degree of rotation which the reamered vessel may achieve in its broken track, which in turn is a measure of turning ability. The formula for the turning circle diameter as a function of reamer width is:

$$D/L_{WL} = 38 * 0.56^{x}$$

where

D = turning circle diameter (m)
L_{WL} = length of waterline (m)
x = reamer width, % of parallel midbody length

It is noted that the non-dimensional turning performance of the reamered vessels show a very clear and logical relationship of decreasing turning diameter with increase in reamer width per unit parallel side.

11.4.3. Vessels without Reamers and with Rounded Shoulders.

Non-dimensional turning diameter of conventional vessels is presented in Figure 11.13 versus the percentage of parallel midbody to waterline length. The data are for full rudder angle, except for the Polar Class which have a rudder angle of 20 degrees.

Two curves are drawn on Figure 11.13, one marked Fully Effective and the other Partially Effective steering arrangements. When a single or twin rudders lie directly behind a single or twin propellers, the steering system is denoted as fully effective. When a single centreline rudder is positioned behind twin wing propellers or the centre propeller of three equally working propellers, the steering system is denoted as partially effective. These curves are intended to indicate overall observed relationships rather than scientifically accurate analysis. The curves reasonably agree with the full scale data, but in order for a comprehensive model to be developed more theoretical and model test experimental background work is required. At this stage this particular model selection can be considered virtually purely empirical. The formulas for the representative lines for effective and partially effective rudders are:

For effective rudders

$$D/L_{WL} = 0.022 * PMB^{1.75} + 3$$

where

PMB = percentage of waterline length representing parallel middle body

For partially effective rudders

$$D/L_{WL} = 0.14 * PMB^{1.5} + 3$$

These two curves therefore suggest that for nine of the conventional vessels in Figure 11.13, turning performance in level ice can be described principally in terms of percentage

parallel midbody length and effectiveness of the steering arrangement.

11.5. Open Water Performance

Calm open water ship performance model is presented in terms of resistance per unit tonne of displacement versus Froude number. Figure 11.14 shows the two lines arrived at for contemporary hull form and for fully formed or conventional hull form.

These curves present clearly the superiority of fully formed rounded hull shapes in terms of open water resistance. however, the model is considered to be very basic only and purely empirical. For further development more theoretical developments and empirical data is required.

11.6. Summary of Performance Predictors

Level Ice Resistance

for chined ships

$$R_1 = 0.08+0.017*C_S*C_H*B^{0.7}*L^{0.2}*T^{0.1}*H^{1.25}* (1-0.0083*(t+30))* *(0.63+0.00074*\sigma_F)* (1+0.0018*(90-\psi)^{1.4})*(1+0.004*(\varphi-5)^{1.5})$$

where

R_1 = resistance in level ice at 1 m/s (MN)
C_1 = resistance coefficient
C_S = salinity coefficient (saline = 1, brackish = 0.85, fresh = 0.75)
C_H = hull condition factor (Inerta = 1, new bare steel = 1.33)
B = ship beam (m)
L = waterline length of ship (m)
T = draft of ship (m)
H = ice thickness (m)
t = ice surface or air temperature (^oC)
ψ = average flare angle in bow region (^{o})
φ = average buttock angle in bow region (^{o})
σ = flexural strength of ice (kPa)

for rounded shoulder ships, using same annotation

$$R_1 = 0.015*C_S*C_H*B^{0.7}*L^{0.2}*T^{0.1}*H^{1.5}* (1 - 0.0083*(t + 30))*(0.63 + 0.00074 *\sigma_F)* (1 + 0.0018*(90-\psi)^{1.6})*(1 + 0.003*(\varphi-5)^{1.5})$$

Notice the differences between the two formulae appearing in the thickness exponent and the influence of the flare angle. The chined ships have a lower thickness exponent and a slightly lower influence of flare angle.

Ridge Penetration Energy

$$E_R = 0.25*A_C*A_R*(1-0.0083*(t+30))*C_S*C_H*(1+0.012*(90-\psi))$$

Where

E_R = energy for ridge penetration (rubble only) (MJ)
A_C = cross-section of main frame (m^2)
A_R = ridge depth * ridge profile length (rubble only) (m^2)
t = ice surface or air temperature (^oC)
C_S = salinity correction
(saline = 1, brakish = 0.85, fresh = 0.75)
C_H = hull condition correction
(Inerta = 1, new bare steel = 1.33)
ψ = average flare angle for bow (^{o})

Turning Circle Diameter

For a vertical sided chined vessel, in level ice of thickness, 60 % of icebreaking capability at 1 m/s,

$$D/L_{WL} = 38 * 0.56^x$$

where

D = turning diameter (m)
L_{WL} = length of waterline of ship (m)
x = reamer width relative to midbody length, PMB (%)

For rounded hull vessels with fully effective rudder(s), in ice thickness of 60 % of icebreaking capability at 1 m/s,

$$D/L_{WL} = 0.022 * PMB^{1.75} + 3$$

where

PMB = percentage of water line length representing parallel middle body

For rounded hull shapes, with partially effective rudder(s), presented similarly as for fully efficient rudders,

$$D/L_{WL} = 0.14 * PMB^{1.5} + 3$$

Open Water Resistance

For chined ships

$$R/Disp = 1.1 * F_n^{1.64}$$

where

R = open water resistance (kN)
Disp = ship displacement (tons)
F_n = Froude number

For rounded ship shapes

$$R/Disp = 0.4 * F_n^{1.68}$$

11.7. Software

The mathematical performance calculation models developed in this project, presented in a summary format in Section 11.7, have been programmed to a software package. This package allows access to level ice resistance ridge penetration energy, turning circle size and open water resistance calculations.

The software is interactive and thus on screen self documenting. It will accept input data as per the Summary of performance predictors in previous section for each model. Using this input data, the program calculates the respective performance component. The user may want to review the block diagram in Figure 11.15, for better understanding of the flow of the program and calculations.

11.8. Conclusions

11.8.1 General

A major step has been taken in developing our understanding of some of the key parameters influencing icebreaker performance. This is the first time that it has been possible to this extent to establish key dependencies for performance based on full scale data. In particular for the level ice resistance and ridge penetration energy the development is new. Also, for turning performance a totally new approach has been established here.

Analysis of full scale trials data for sixteen of the worlds major icebreakers, incorporating most design developments of the past twenty years, has provided many important new insights into the influence of ship design and environmental parameters upon performance.

Performance predictors for preliminary design have been developed for the performance components of level ice resistance, propulsive performance, hull lubrication, ridge resistance, turning in ice and open water resistance.

11.8.2. Level Ice Resistance

Low level ice resistance is achieved by chined designs and short bows with flat wide opening frames (= large flare angle) and a shallow buttock angles. This is clearly and quantitatively confirmed based on extensive interpretation of full scale data.

Ice resistance increases with steepening angles of frames and buttocks. In particular, the steep shoulder regions of fully formed rounded ship shapes increased resistance significantly.

A new practical method is presented for determining the influence of environmental parameters on level ice resistance. It includes the influence of temperature, hull condition, ice strength, water salinity and ice/snow thickness.

11.8.3. Ridge Penetration Energy

The energy to penetrate the rubble portion of a ridge depends directly on the size of the hole a ship has to make through the ridge as well as on the cross-section of the ridge being penetrated.

The influence of hull shape and environmental conditions on ridge penetration energy has been demonstrated from full scale data for the first time.

The lowest penetration energy is achieved by a bow form that pushes ice down rather than sideways. This is represented by Oden with wide opening flat frames. Steeper angles such as shoulder regions of fully developed rounded hull shapes require considerably more energy to penetrate ridges.

Penetration energy is also dependent on the air temperature, water salinity, hull condition and the volume of rubble in the ridge. A method is given to calculate the ridge penetration energy in this paper.

11.8.4. Turning Circle Size

The study has shown that the turning ability in ice of vessels with reamers is dependent principally upon the ratio of reamer width to the length of parallel side. Turning diameter decreases predictably with increase in this ratio.

The non-dimensional turning performance of conventional vessels in level ice is shown to be strongly dependent upon the ratio, length of parallel waterline/waterline length, and upon the effectiveness of the steering arrangement. Turning performance is enhanced by decrease in the length of parallel side and increase in steering system effectiveness.

Ship length/beam ratio, which traditionally has been used as a design index for turning of vessels in open water is not a fundamental governing parameter for turning performance in ice. Turning in ice is clearly more dependent upon local geometry about the waterline and how this affects rotation in the broken track, than upon overall dimensions of the waterline.

Comparable good turning ability can be achieved either by a ship with no parallel middle body or by a ship which has a long parallel middle body and a large reamer.

11.8.5. Open Water Resistance

Specific resistances for conventional, fully formed hulls, show the same parametric influences as the contemporary hull forms, but are much lower. Specific resistance for a conventional vessel can be less than 50% of a contemporary vessel of the same size and proportions. At lower speeds even bigger difference exists.

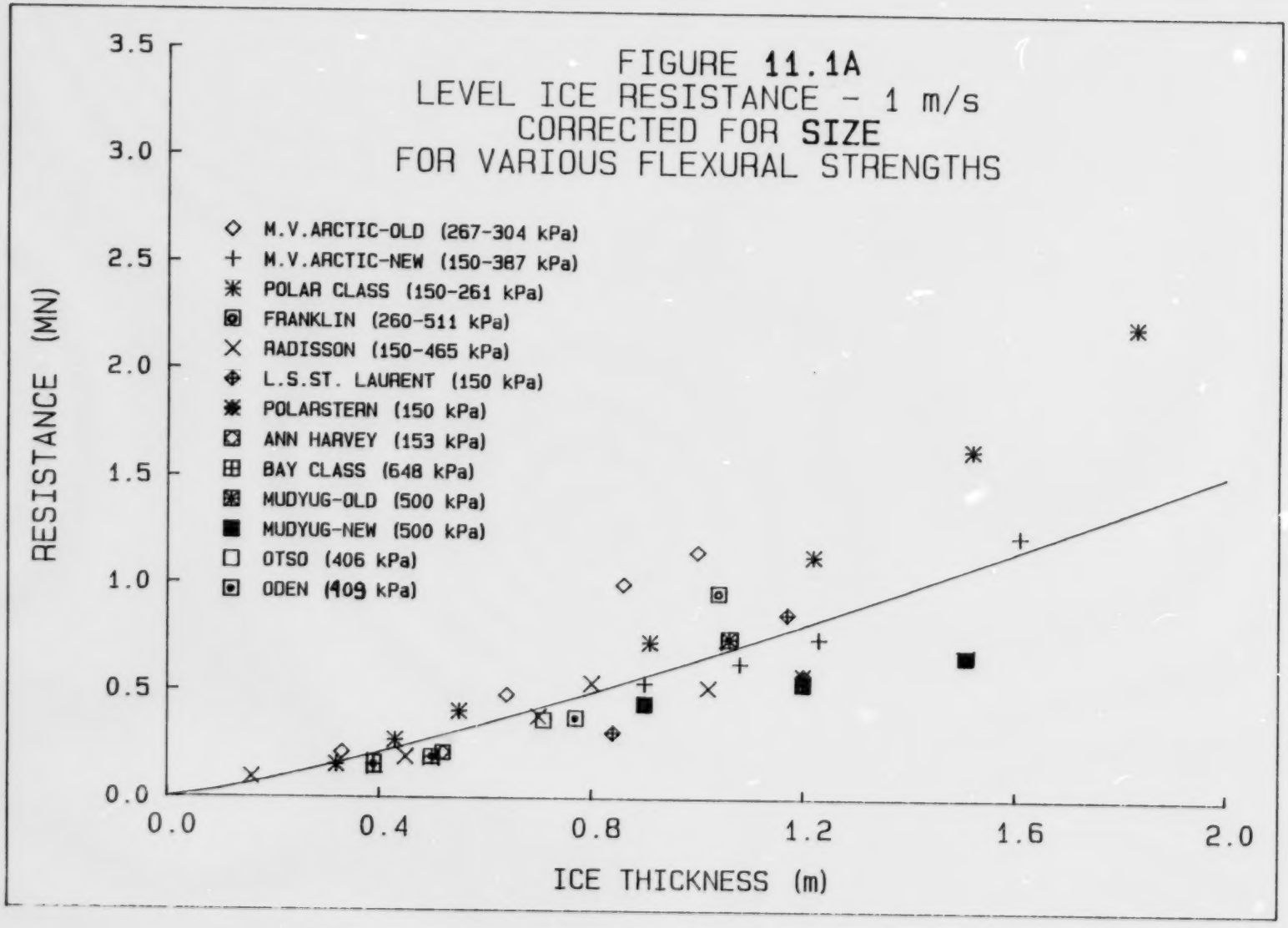


FIGURE 11.1A
LEVEL ICE RESISTANCE - 1 m/s
CORRECTED FOR SIZE
FOR VARIOUS FLEXURAL STRENGTHS
M.V.ARCTIC-OLD (267-304 kPa)
M.V.ARCTIC-NEW (150-387 kPa)
POLAR CLASS (150-261 kPa)
FRANKLIN (260-511 kPa)
RADISSON (150-465 kPa)
L.S.ST. LAURENT (150 kPa)
POLARSTERN (150 kPa)
ANN HARVEY (153 kPa)
BAY CLASS (648 kPa)
MUDYUG-OLD (500 kPa)
MUDYUG-NEW (500 kPa)
OTSO (406 kPa)
ODEN (409 kPa)
RESISTANCE (MN)
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
0.0
0.4
0.8
1.2
1.6
2.0
ICE THICKNESS (m)

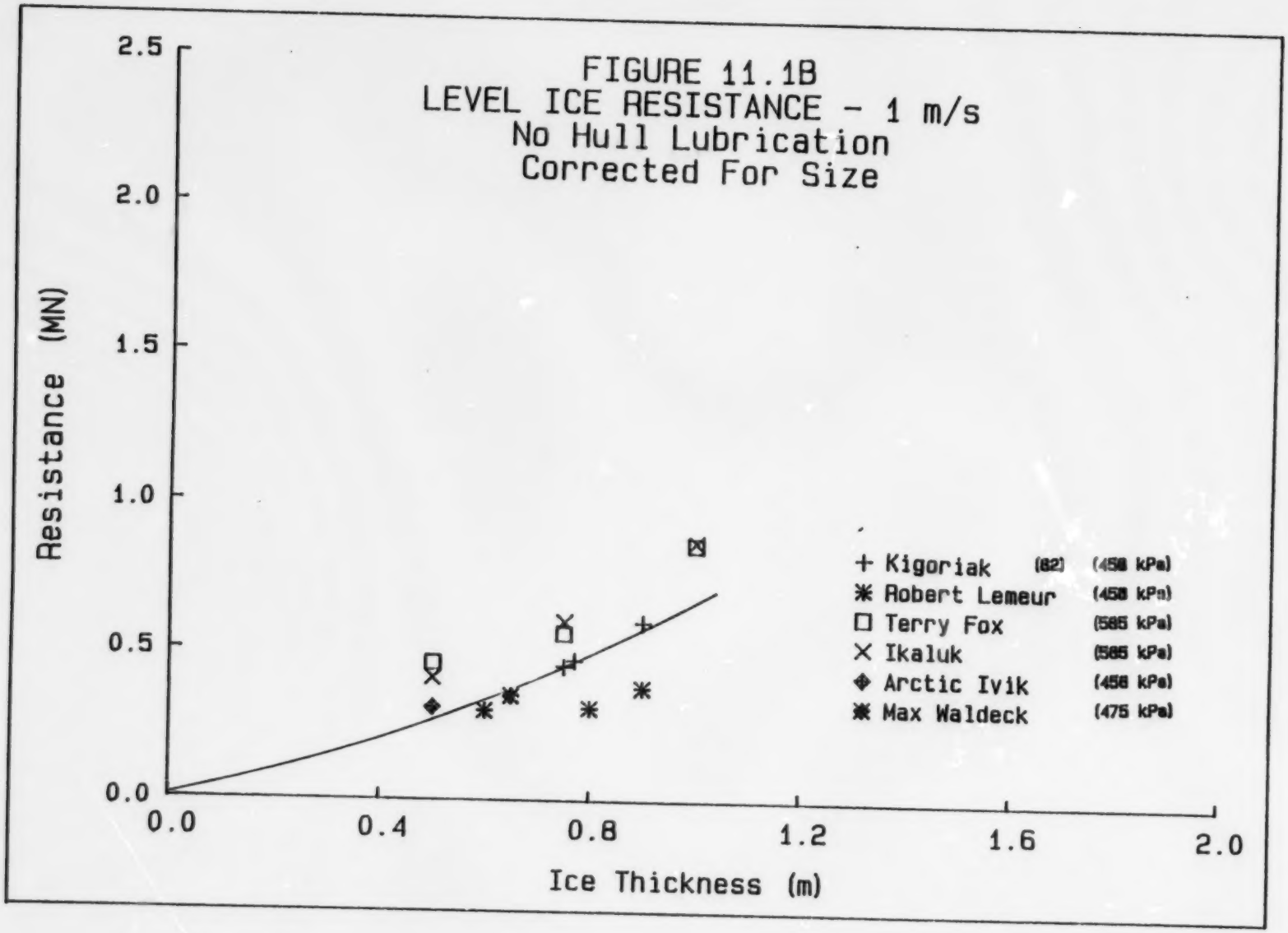


FIGURE 11.1B
LEVEL ICE RESISTANCE - 1 m/s
No Hull Lubrication
Corrected For Size
Resistance (MN)
2.5
2.0
1.5
1.0
0.5
0.0
0.0
0.4
0.8
1.2
1.6
2.0
Ice Thickness (m)
+ Kigoriak (82) (458 kPa)
* Robert Lemeur (458 kPa)
□ Terry Fox (585 kPa)
× Ikaluk (585 kPa)
◆ Arctic Ivik (458 kPa)
* Max Waldeck (475 kPa)

FIGURE 11.2
HULL CONDITION CORRECTION FACTOR

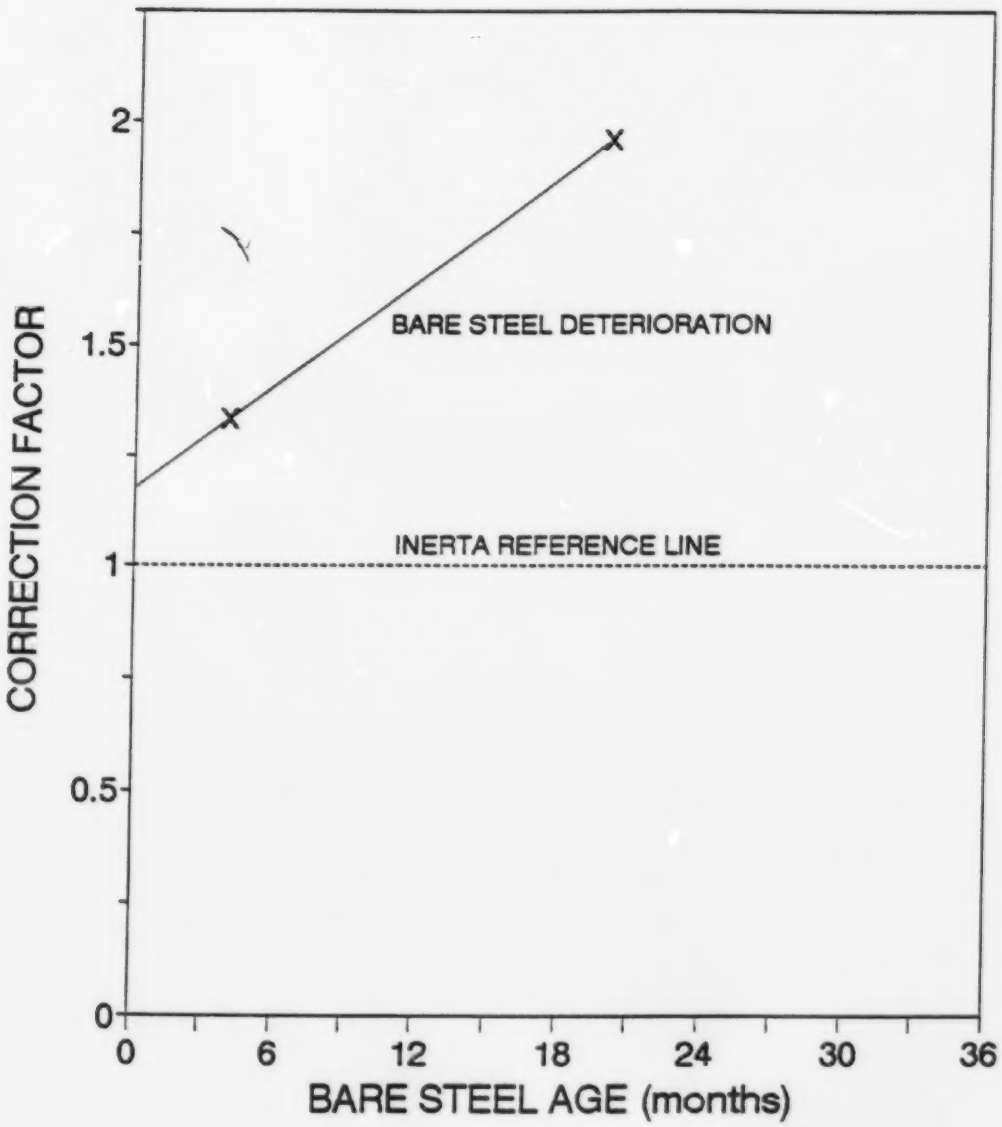


FIGURE 11.3
INFLUENCE OF TEMPERATURE ON FRICTION

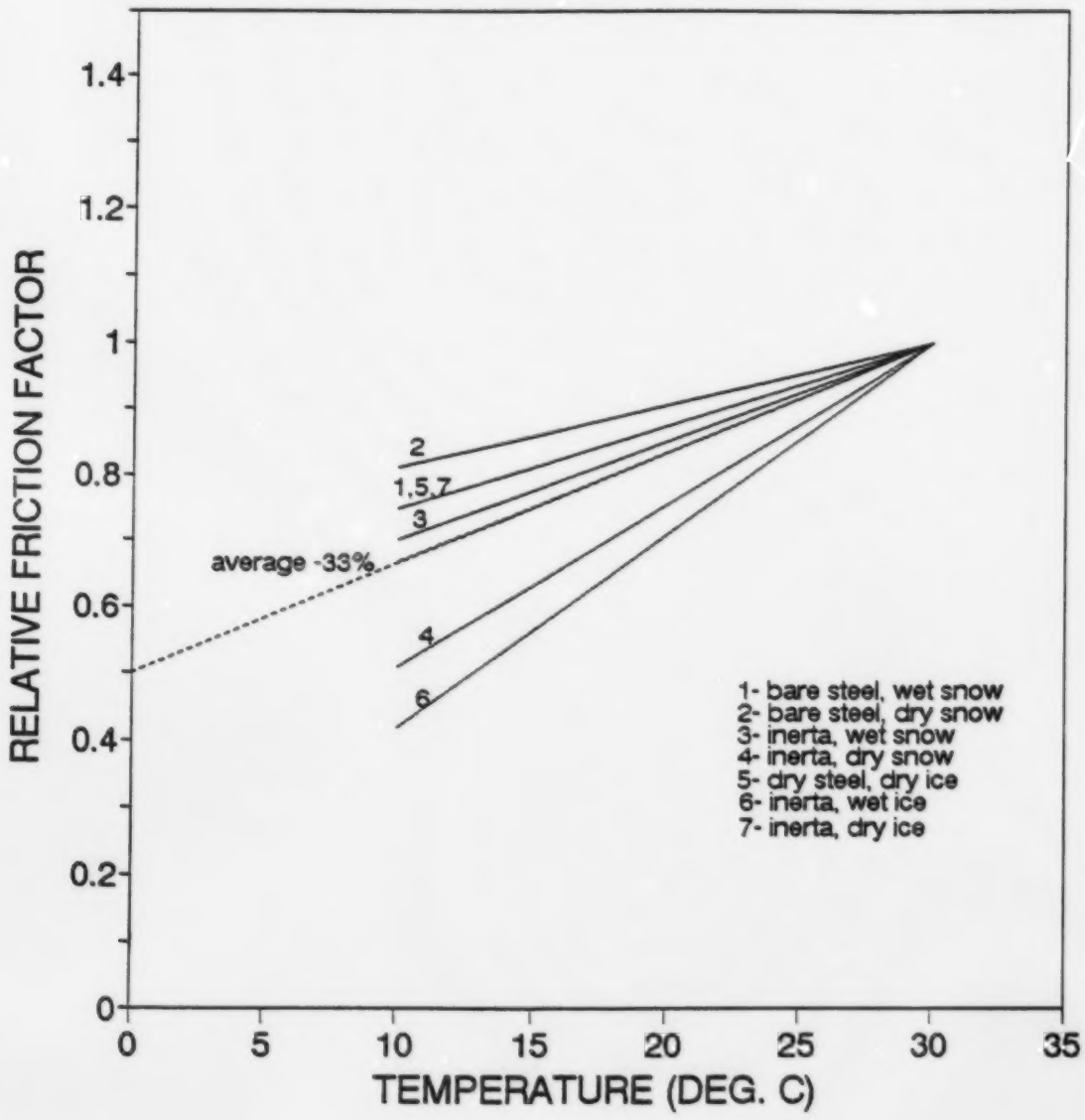


FIGURE 11.4
RESISTANCE CORRELATION WITH FRICTION

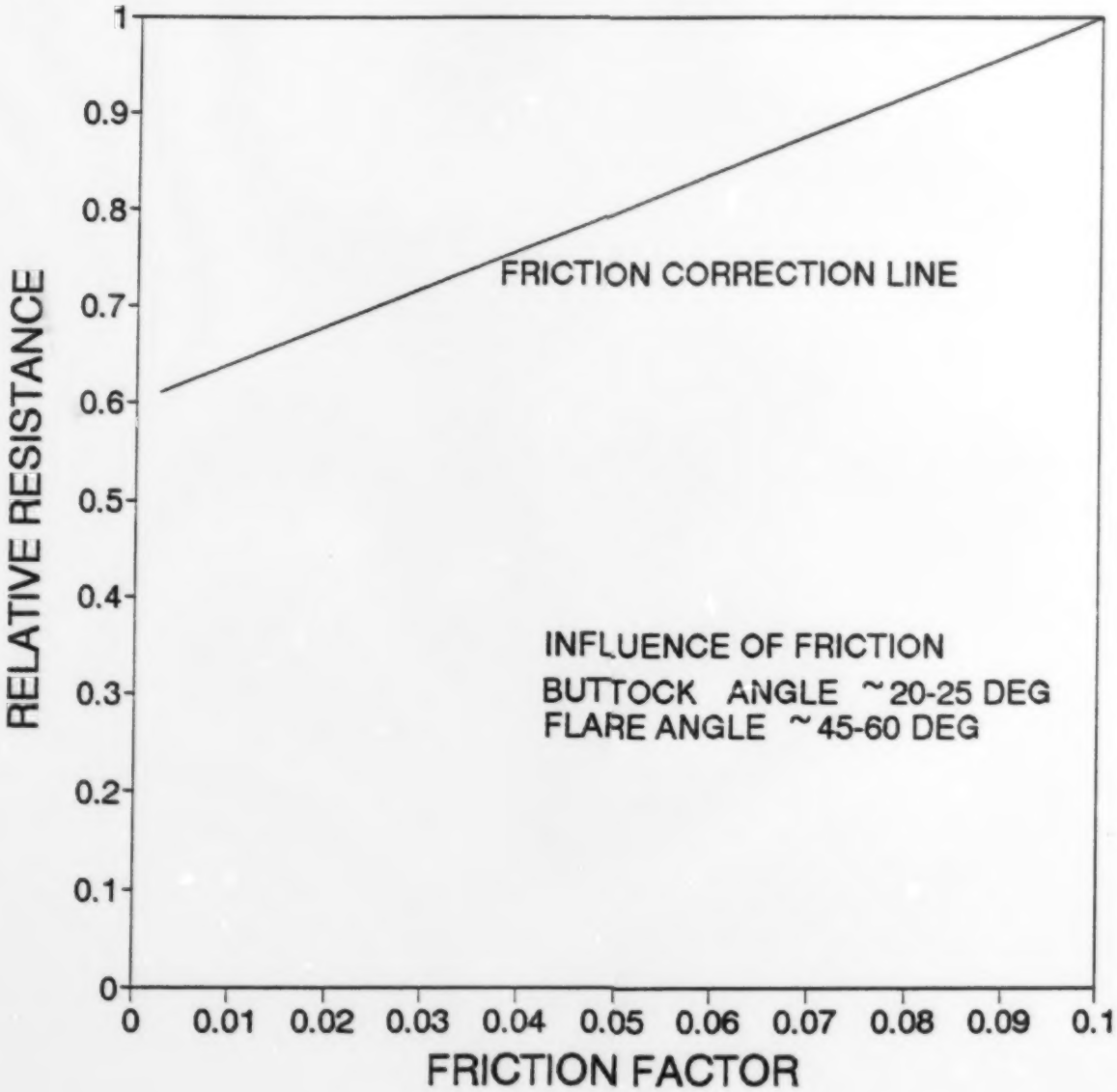


FIGURE 11.5
ICE STRENGTH CORRECTION FACTOR

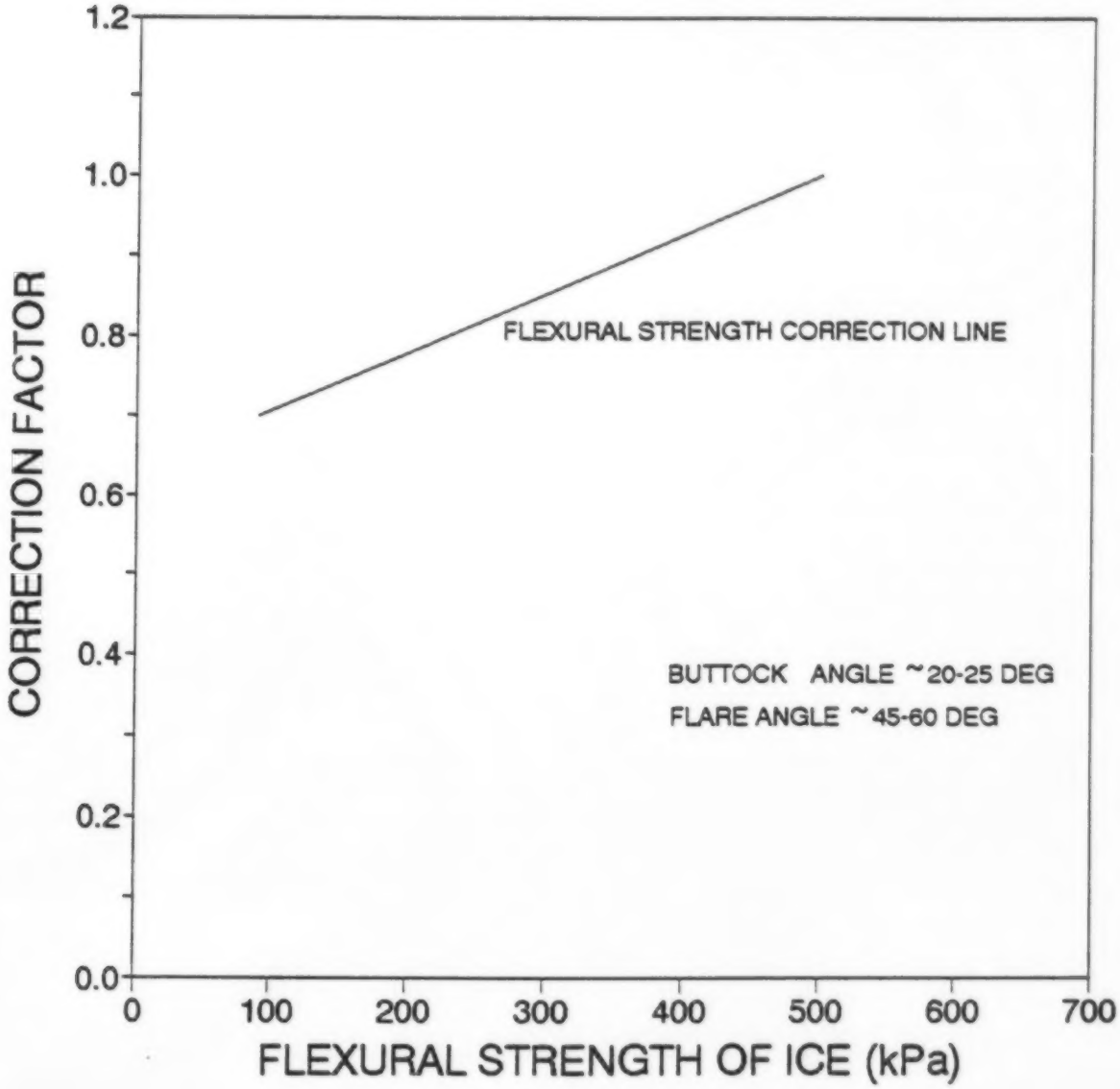


FIGURE 11.6
WATER SALINITY CORRECTION

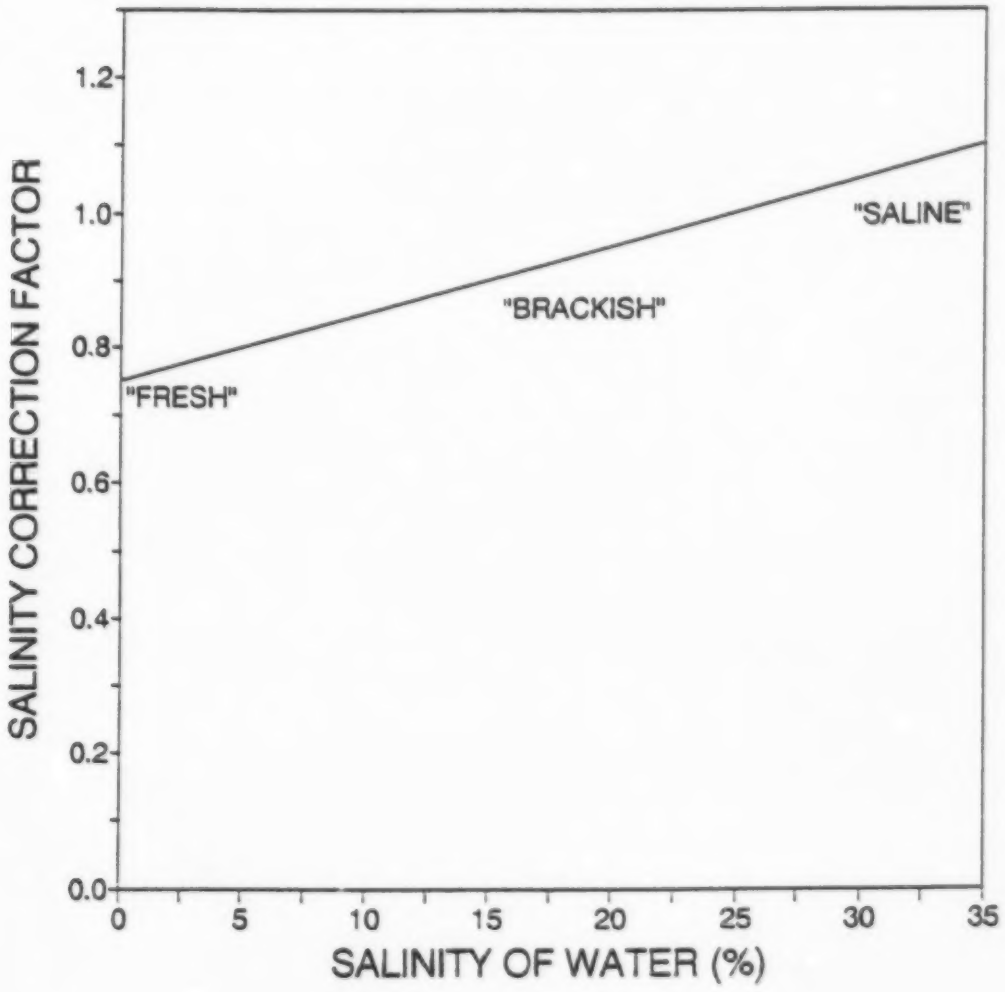


Figure 11.7
Corrected Resistance, Chined Hulls

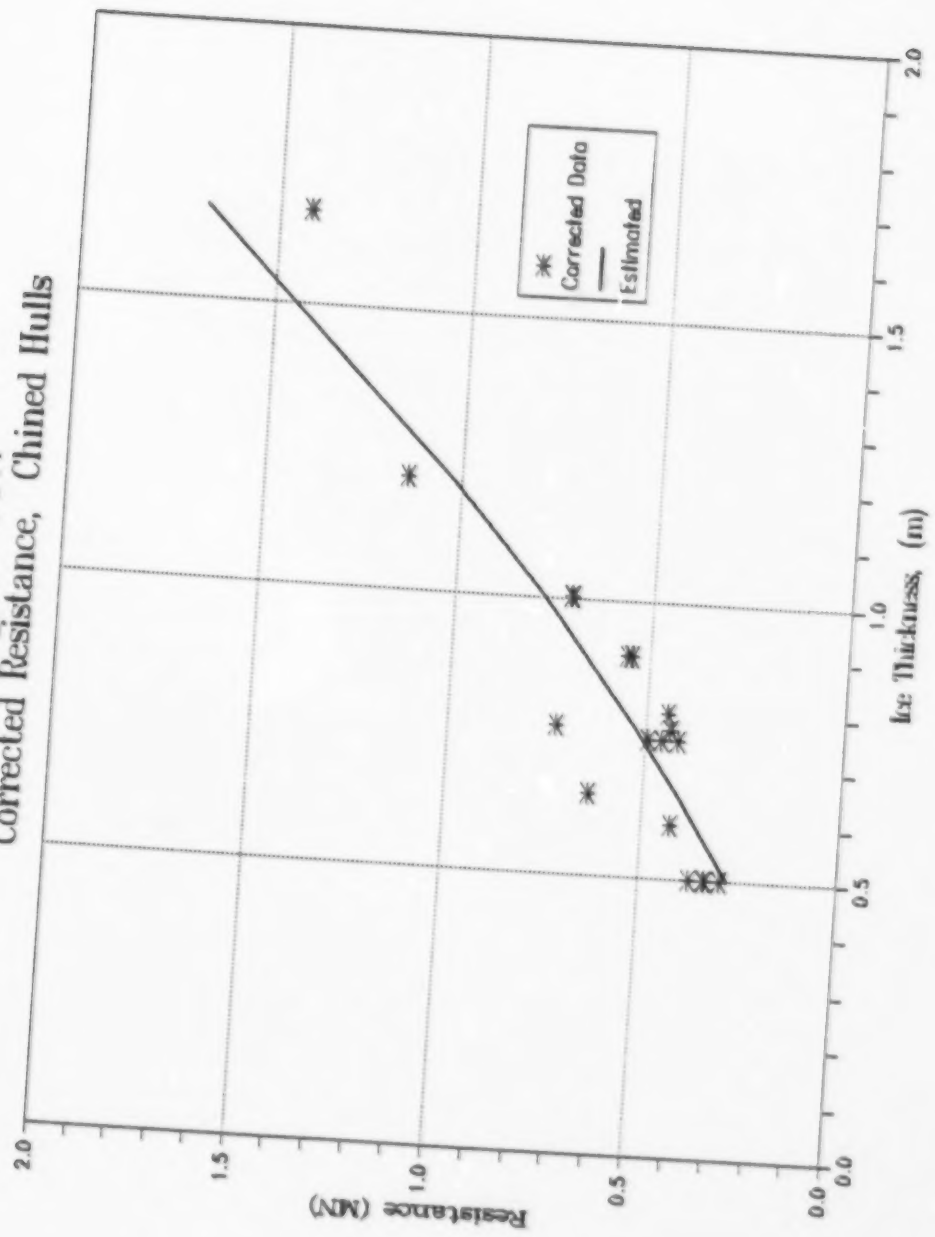


Figure 11.8
Corrected Resistance, Rounded Hulls

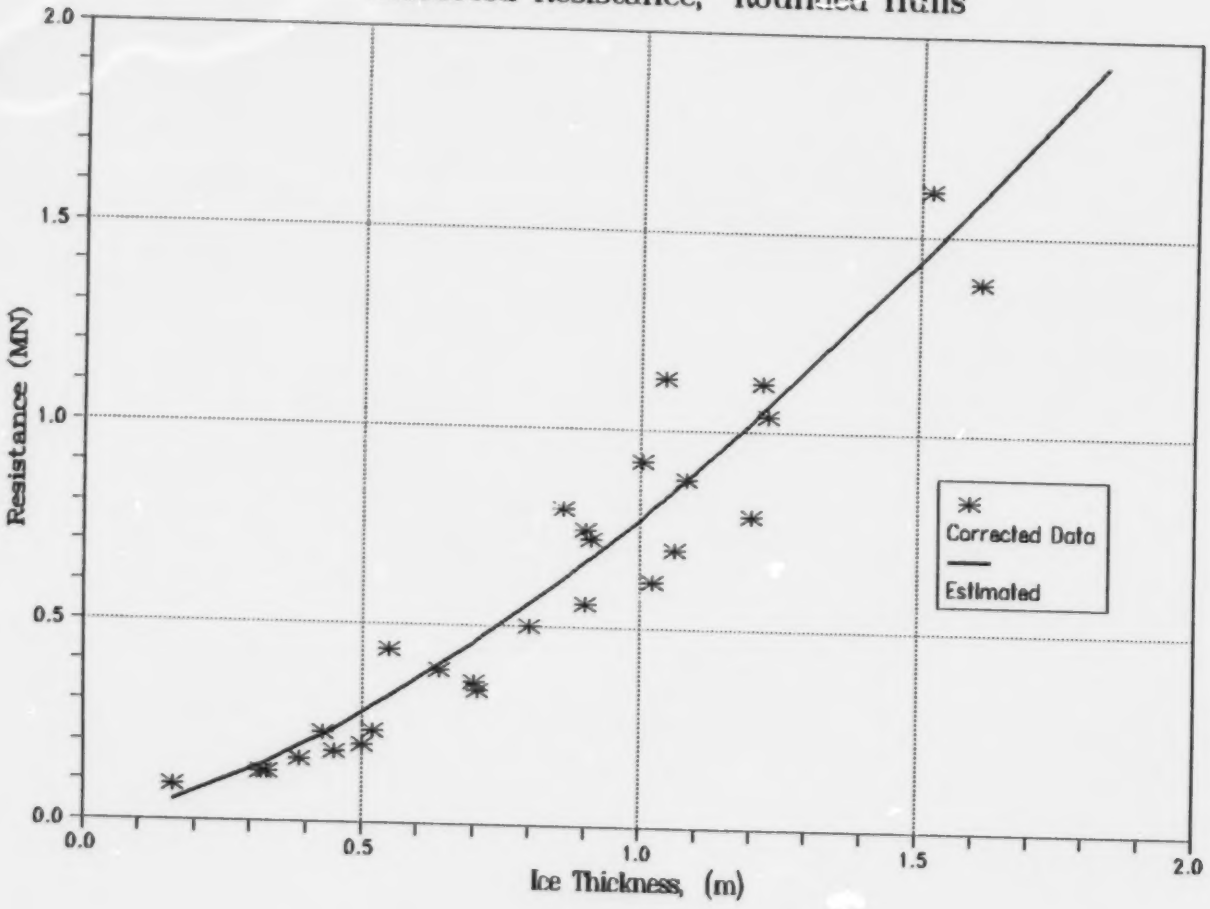


Figure 11.9.
Buttock Angle Vs Level Ice Resistance

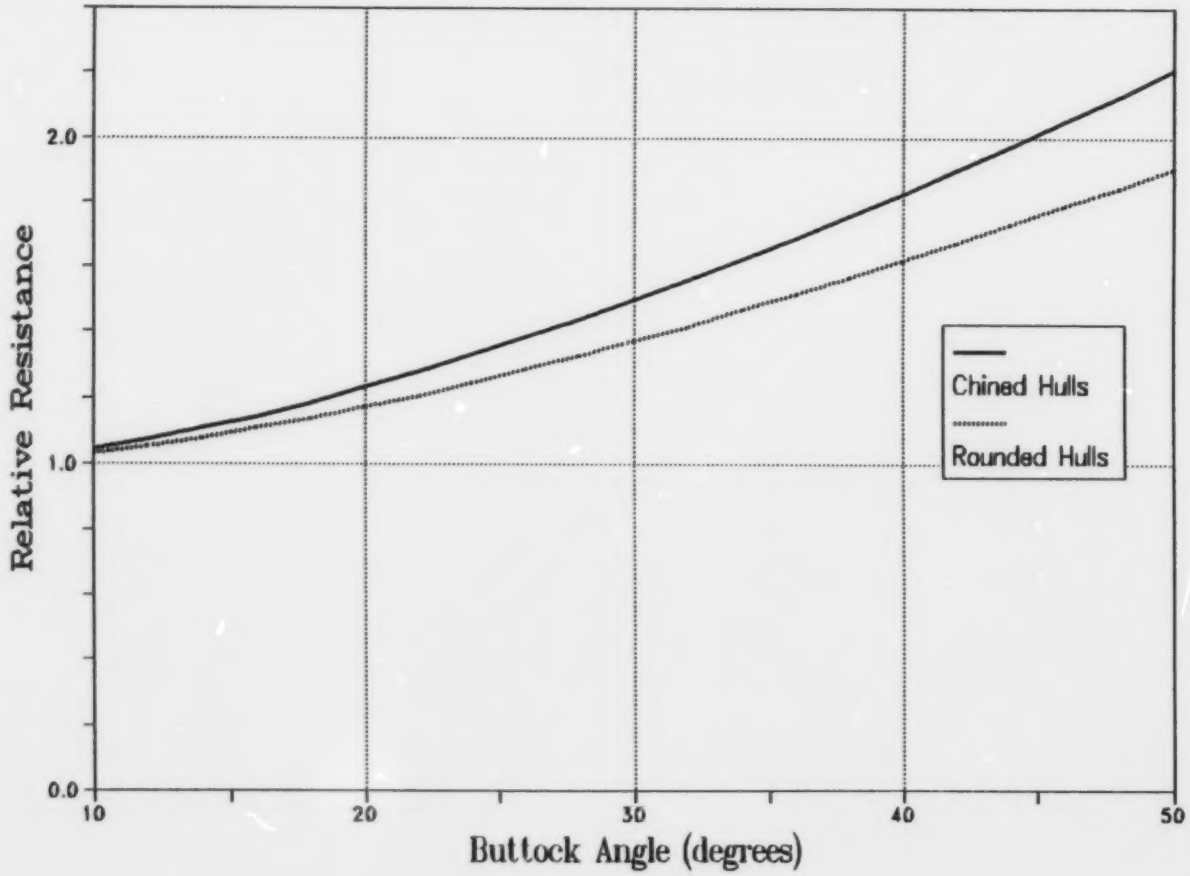


Figure 11.10
Flare Angle Vs Level Ice Resistance

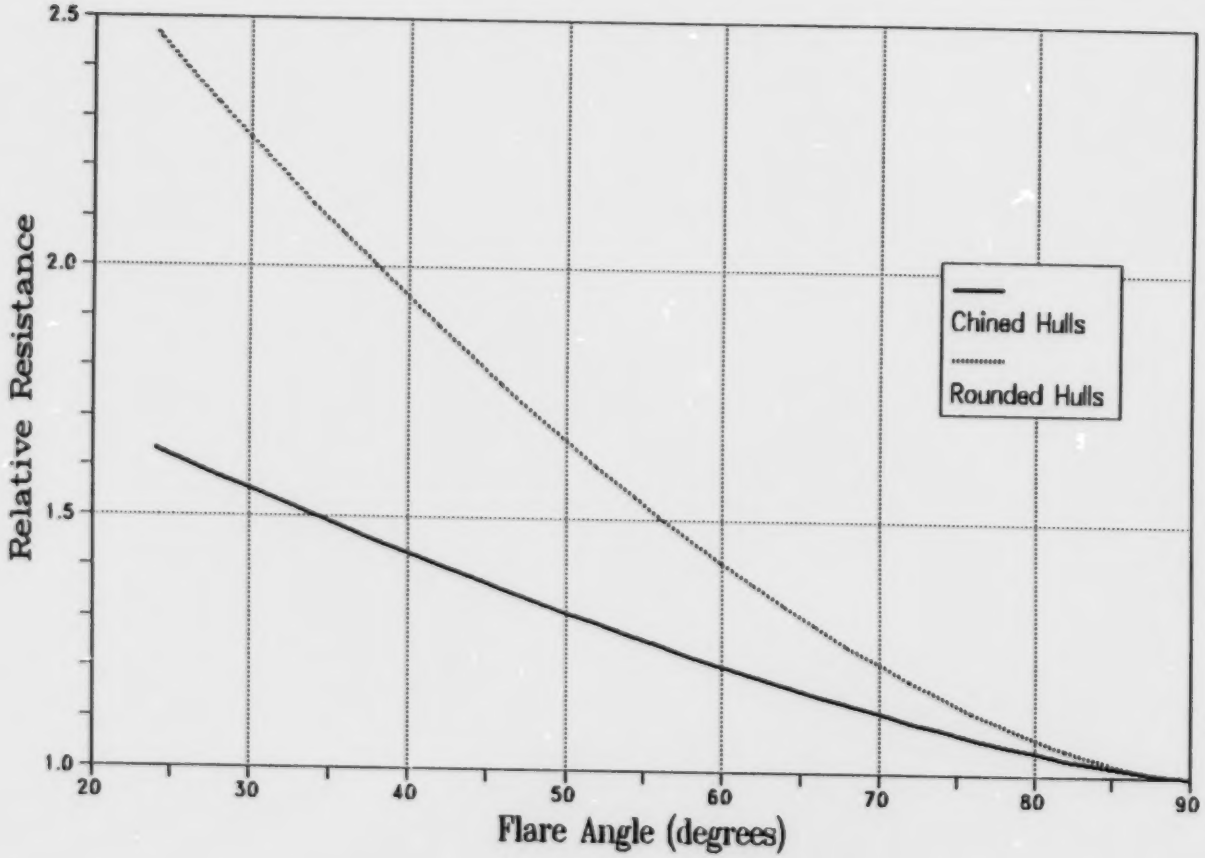


Figure 11.11
Ridge Penetration Energy Vs Flare

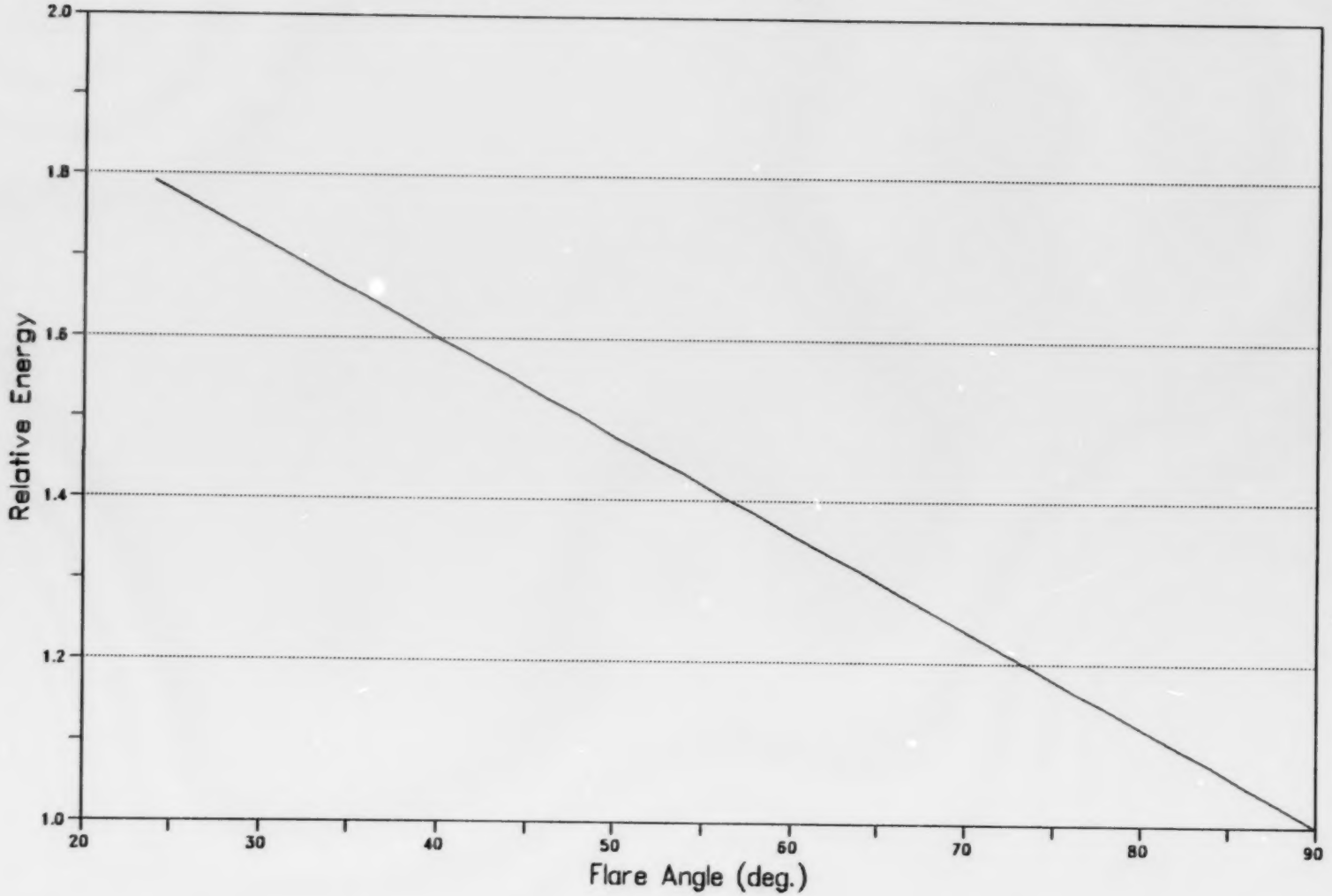


Figure 11.12
Turning Circle Size Vs Reamer Width

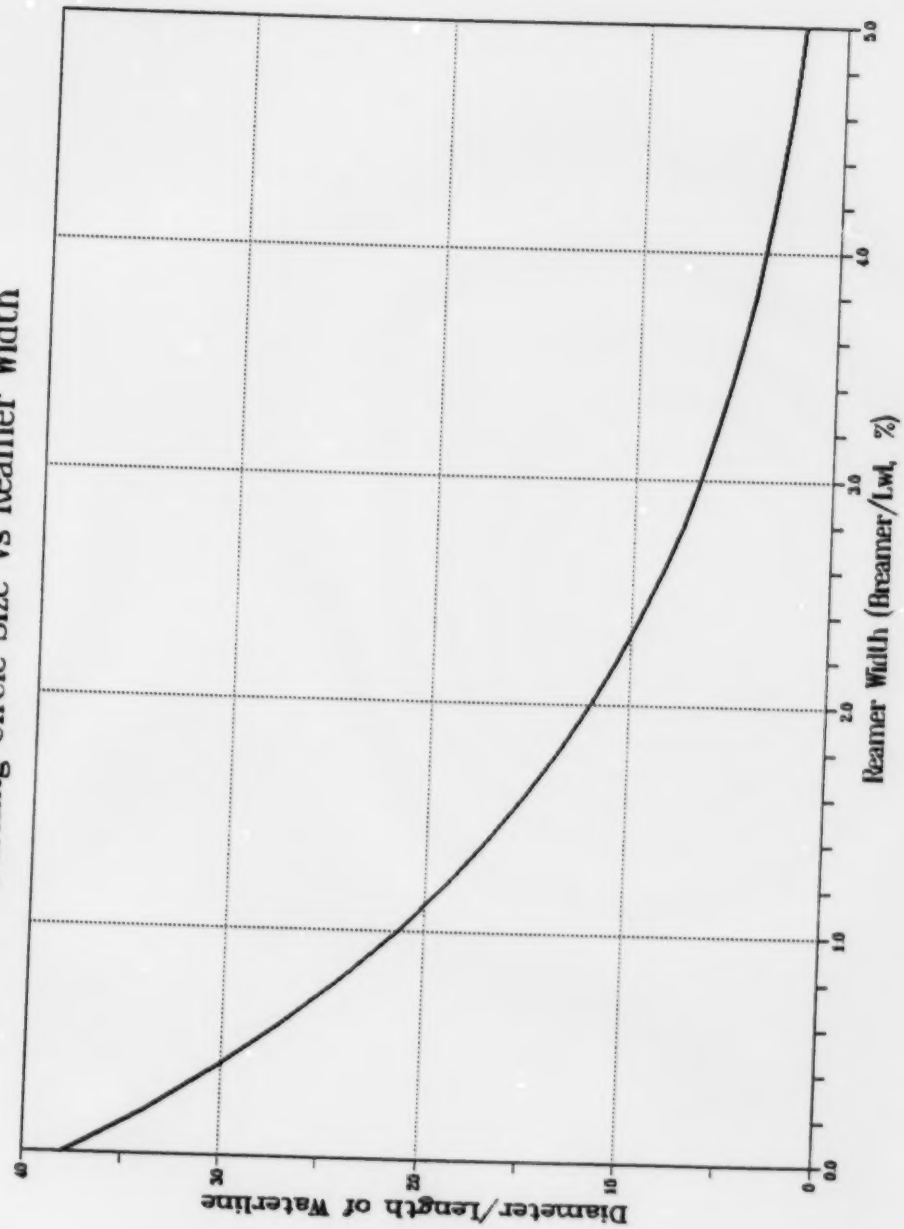


Figure 11.13
Turning Circle, Round Hull Shapes

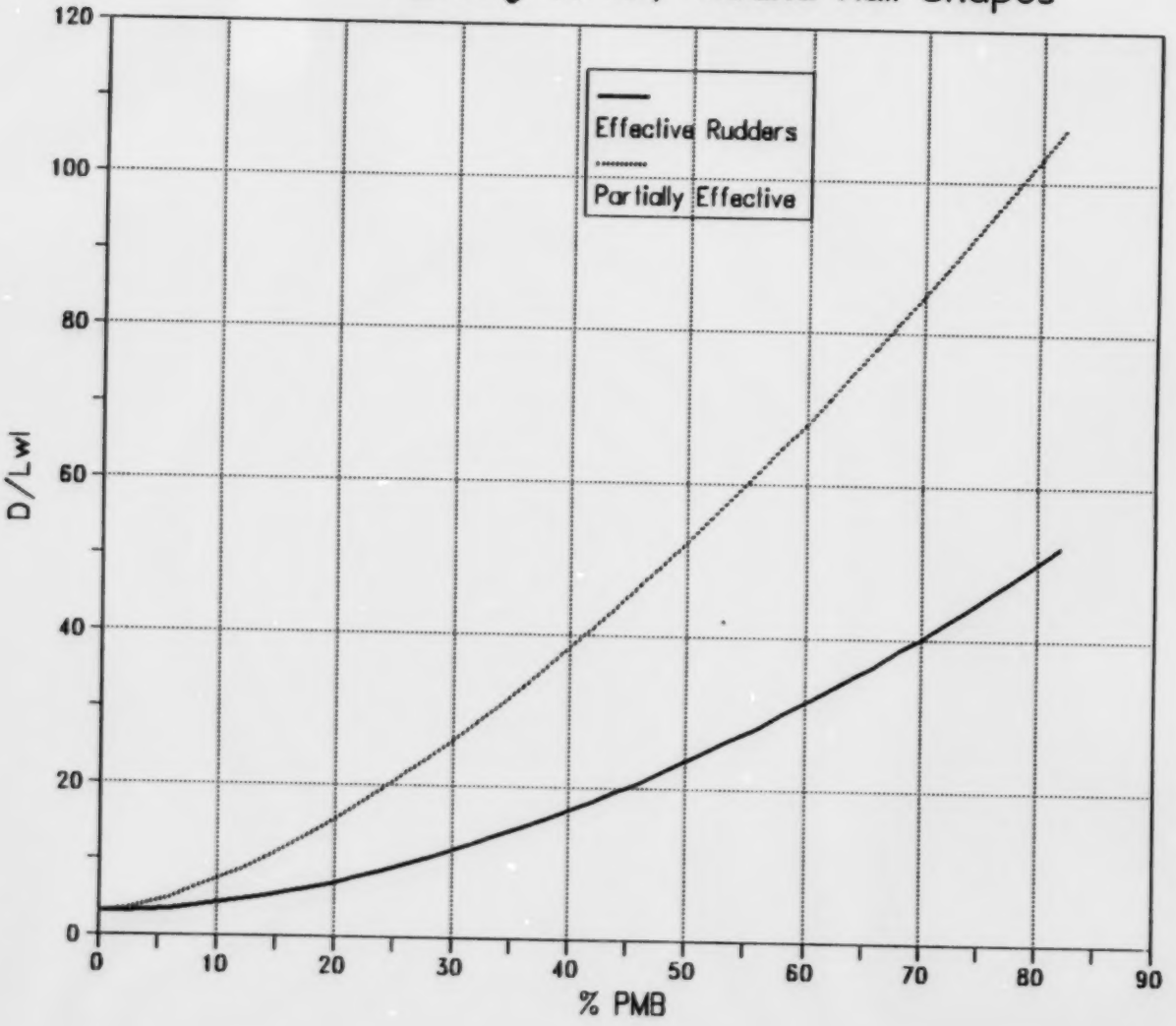


Figure 11.14
Open Water Resistance

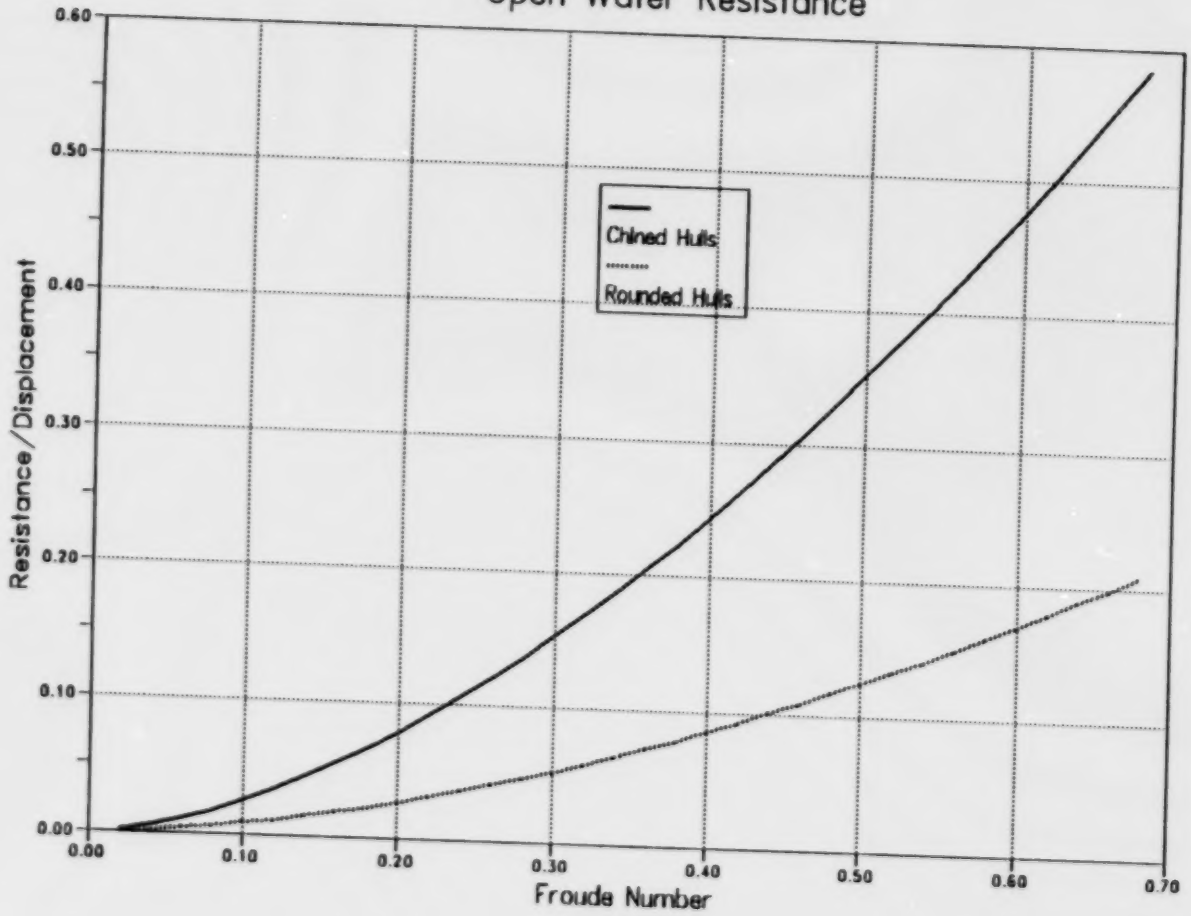
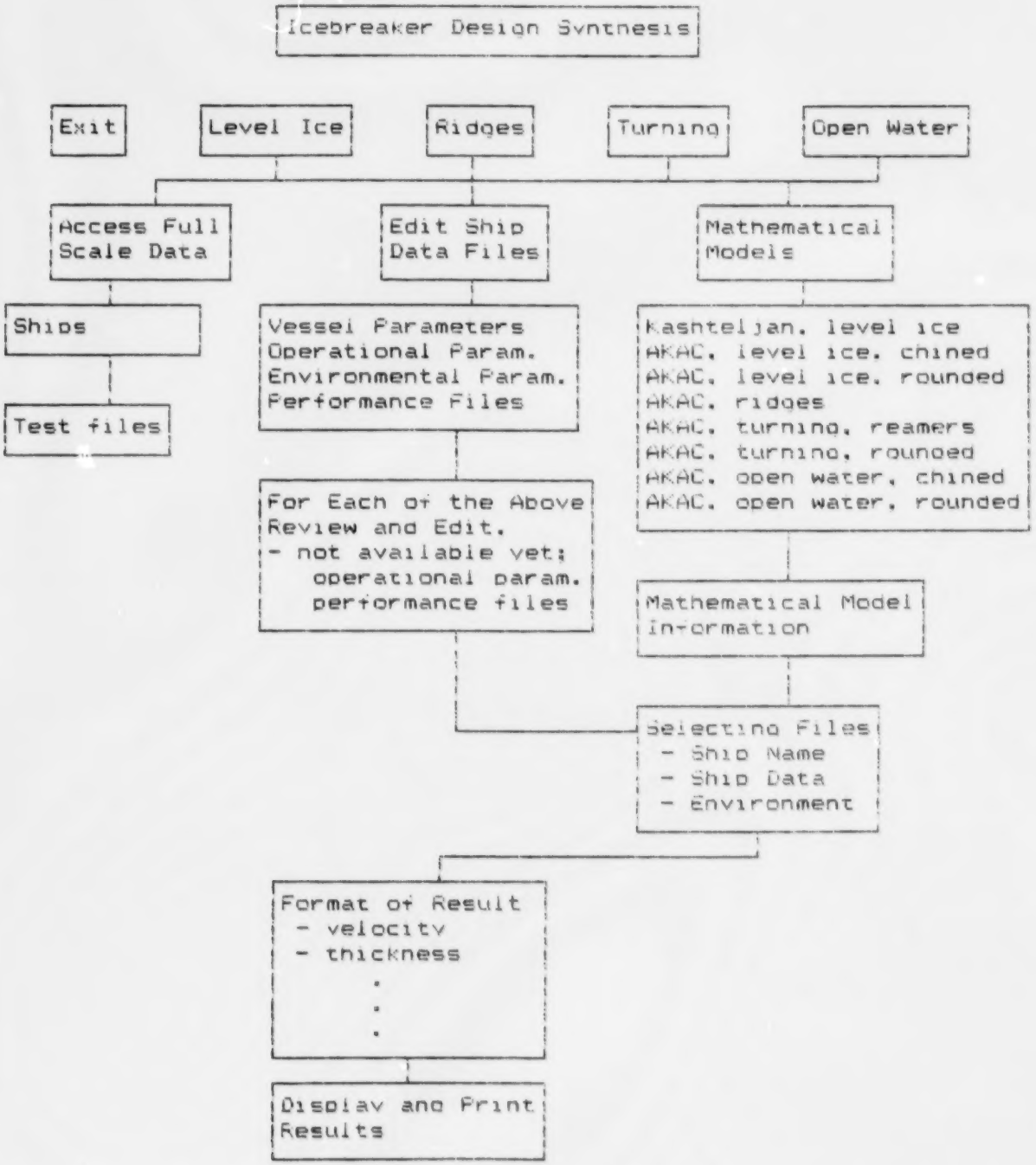


Figure 11.15

Block Diagram for Mathematical Model Software



12 CONCLUSIONS

12.1 Overview

The conclusions fall into two broad categories:

a. Specific results from the data and interview analysis relating performance to particular design features, and the overall ability of the vessels to accomplish their mission roles.

b. The degree of success of the methodologies adopted in the study.

Figure 12.1 provides a schematic linking the key elements in the project. In this study the full scale data have been analysed and parametric dependencies determined. The results from the data analysis have been used to build performance prediction models. The operator interviews have also been analysed to determine the qualitative role of design features on performance while carrying out their missions.

The two streams are brought together in the following subsections to provide a practical set of information for the designer and operator.

12.2 Vessel Performance and Design Features

12.2.1 Design Features

Bow

Data Based

a. Level ice resistance decreases with increase in average flare angle and with decrease in average buttock angle.

b. Vessels with high bow flare angles use less energy in penetrating ridges than those with low flare angles.

Interview Based

c. Bows with a moderate V shape offer good directional control in both level ice and ridge breaking, whereas bows with very high or very low flare angles have poor directional control in ice.

d. Vessels with high flare angles are able to break out of channels readily, whereas those with low flare angles are not.

e. The bow shapes of all the icebreakers are less than ideal for extreme open water conditions. Bows with high flare angles and shallow stem angles tend to pound. Those with low

flare angles but little above-water flare are wet. Traditional icebreakers with rounded hulls tend to have large roll and pitch motion and acceleration responses in heavy seas.

Bow Stopper

Interview Based

a. Deeply immersed small stoppers rarely contact solid unbroken ice.

b. Blunt angle stoppers with vertical profiles cause high decelerations in ridges.

c. If the bow stopper is too far forward and close to the waterline, the vessel is stopped before the maximum vertical icebreaking force can be developed. In addition the stopper may trap floes and carry them along with the ship.

d. Wide deep wedges are effective in clearing ice from the wake. The effectiveness is reduced at higher speeds.

Chines

Data Based

a. The level ice resistance of vessels with chined bows increases slower with increasing ice thickness than for fully formed bows.

b. Chined hull forms, particularly when associated with bow wedges and/or reamers, have significantly higher open water resistance than fully formed hulls of the same size and proportions. In the mid-speed range, chined hull resistance can be more than twice the fully formed hull resistance.

Reamers

Data Based

a. Greatly assist turning ability in ice. Turning ability of reamered vessels is determined predictably by the ratio of reamer width/length of parallel side. Vessels with reamers and long parallel side can have the same good turning ability as conventional vessels with little or no parallel midbody.

Interview Based

b. Are effective in reducing midbody friction.

c. Increase the resistance astern, particularly in pressure.

Length and Shape of Parallel Midbody

Data Based

a. The turning diameter in ice of conventional vessels without reamers increases significantly with increase in the ratio, length of parallel midbody/waterline length.

Interview Based

b. Increasing length increases friction resistance in pressured ice and ridges.

c. Vessels with large diameter bilges can experience large amplitude rolling which is uncomfortable even with the reduction from a passive flume stabilization system.

d. Long transitions from the bow to the midbody with low flare angles cause a vessel to stick in thick ice and heavy ridging (shoulder wedging).

Propulsion System

Data Based

a. At normal icebreaking speeds ahead, ducted propellers consistently provide higher propulsive effectiveness than open propellers.

b. Open controllable pitch propellers can attain similar propulsive effectiveness at bollard but relatively higher propulsive effectiveness at higher speeds than do open fixed pitch propellers.

Stern Arrangement

Interview Based

a. The astern performance in ice of vessels with square or transom sterns is generally poor.

b. Vessels with sterns of icebreaking shape similar to the bow, generally break ice and manoeuvre well astern.

c. Clearance above the propeller is essential to minimize ice/propeller interaction.

d. Propeller nozzles protect the propeller from interaction with large pieces of multi-year ice, but performance may be degraded by blockage.

e. Open propellers are effective in very thick ice (ridges, broken or pressure ice) as they suffer less from thrust degradation than ducted propellers. However, in multi-year ice, open propellers are prone to damage.

f. Propellers which are not well protected by the hull have significant ice interaction. This limits manoeuvring and astern performance.

Propeller and Rudder Arrangement

Data Based

a. Rudders are most effective when directly behind propellers. The turning circle diameter in ice of a conventional vessel without reamers and with the rudder(s) directly behind the propeller(s) can be one half that of the same vessel with the rudder offset from the propellers. Moreover, some single rudder, twin screw ships have significant lag in helm response, which may contribute to erratic course keeping in broken ice, if coupled with unfavourable bow angles.

Interview Based

b. Triple screw ships have good manoeuvrability when using differential thrust, particularly astern when the rudder is centred.

Propulsion Control

Interview Based

a. A full ahead/astern thrust time of 10 to 12 seconds is required for aggressive icebreaking to minimize the risk of getting stuck in ridges (extraction) and for fast response to avoid damage.

Auxiliaries for Friction Reduction

Data Based

a. The hull lubrication system of low pressure pumping of water onto the ice ahead of the bow/ice interface is the most efficient friction reducing system investigated in this study. The shaft power saving can be many times system power. The system of high pressure air/water jets along the bow/ice interface also provides significant overall power savings.

Interview Based

b. The air bubbler system will decrease the amount of ice in the track and reduce the amount of propeller/ice interaction.

Heeling System

Data based

a. Heeling the ship can produce significant reductions in turning diameter in ice.

Interview Based

b. If heeling the ship is used for reduction in turning diameter in ice, the time to heel the vessel should be of the order of 2 minutes or less.

c. Active heeling systems with times of less than 5 minutes are used for extraction from heavy ridging. This occurs infrequently with a good low friction hull coating.

d. Active systems are useful for maintaining progress in extreme conditions such as rubble fields and high friction, on a continuous cycling basis. Cycling times should be about two minutes or less.

e. Flume passive systems or Intering systems are effective in reducing severe rolling in open water, but on vessels with large bilge radii the rolling is still uncomfortable.

Hull Coating

Data and Interview Based

a. An effective, intact, high impact and low friction coating improves performance significantly in most performance categories and is considered essential for effective and efficient operations in ice.

b. A stainless steel band at the waterline is effective in friction reduction.

12.2.2 Mission Roles

General

Interview Based

a. Despite deficiencies in some aspects of performance for all the vessels, masters are able to perform assigned mission roles by operating their vessels to take advantage of superior aspects of performance. Where the vessel has no superior aspects of performance in the environmental conditions in which she operates, the ability to perform the mission can become marginal.

b. The features selected for the mission role must recognize the impact of environmental conditions.

Ice Escort

Interview Based

a. Bow shape, bow wedges, bubblers, rise of floor midships and stern configuration all contribute to a wide clear track.

b. Depending upon a vessel's manoeuvring capabilities ahead and astern, backing down or turning around can both be effective manoeuvres in assisting a beset vessel.

c. Towing of smaller, low powered vessels in heavy ice conditions can be the only efficient way to maintain forward progress.

Ice Management

Interview Based

a. Vessel squat can degrade performance capabilities in shallow water

b. The large wake common on most icebreakers is useful for breaking a wider track in lighter ice conditions but is detrimental in restricted waterways where it may damage shore facilities

Transit

Data Based

a. In high ice concentrations (up to about 8 tenths coverage), vessels are able to maintain average speeds in excess of 75% of their maximum open water speed. The presence of old ice, the manoeuvrability of the vessel and econonical power levels are factors in determining the actual speed.

12.3 Methodologies

12.3.1 Interview

a. The results of the interview agree with the trends established form the full scale results.

b. The interview results provide performance information that is not available from the full scale trials which are limited in scope.

c. Allowing for the bias of the masters related to their own operational backgrounds, there was good aggreement on the role of the design features for one ship when evaluated by different masters.

12.3.2 Data Analysis

a. The method of data analysis used, which puts all data on a common data base, permits a genuine comparison of icebreaker performance in specific performance categories and allows the key dependencies of environmental and ship design parameters upon performance to be determined.

b. The analysis shows many of the key influences of design parameters and features on performance in specific performance categories. The design parameter range covered is very large and incoporates virtually the whole range of parameters and features currently used on icebreakers.

c. The methodology developed for bringing all trials data to a common environmental base can be used to make realistic comparisons between vessels tested in different conditions.

12.3.3 Models

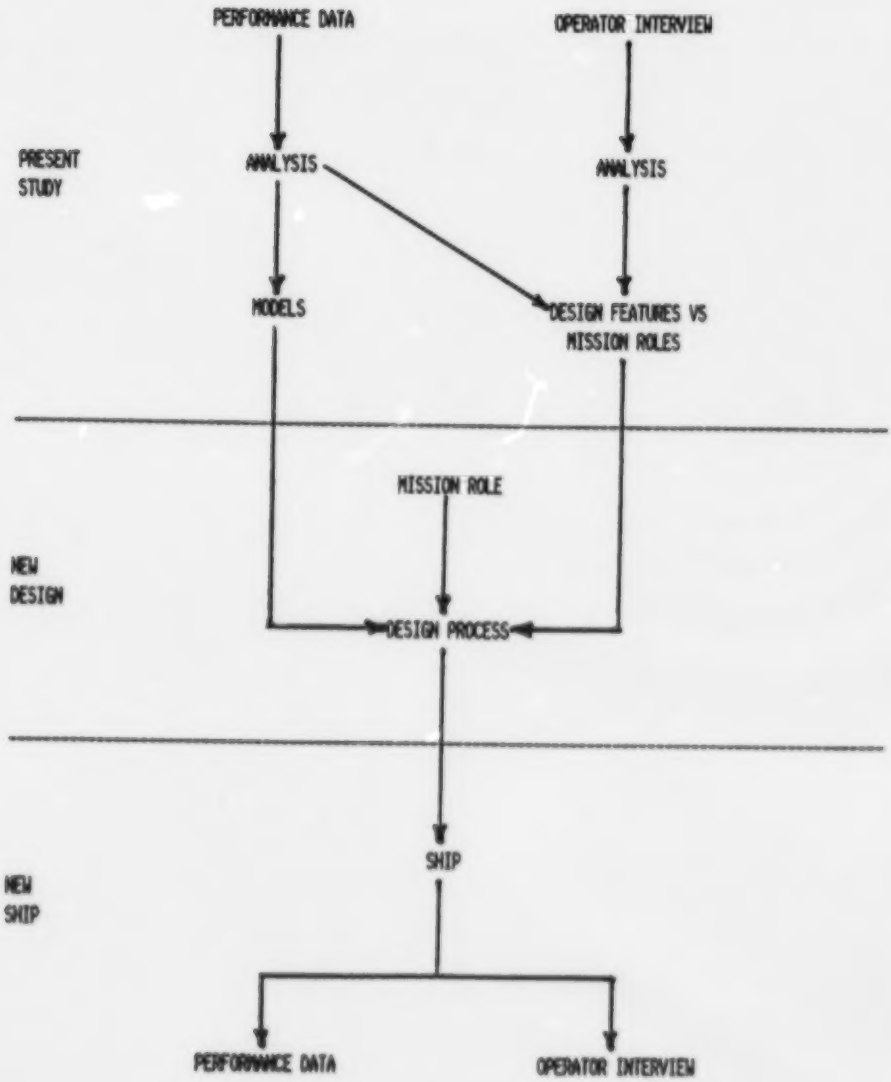
a. The models provide the designer with a tool to predict the performance of a vessel in many performance categories. They are valid for different combinations of the wide range of design parameters and features covered in the study. The models are based on full scale ship performance and therefore predict ship performance directly.

12.3.4 Overall Methodology

a. The process of combining the interview and data analysis in a single project has proved highly successful. The interview data have complemented the limited scope of full scale data and have provided the opportunity to make overall evaluations of the vessels and their design features.

FIGURE 12.1

USE OF STUDY IN DESIGN PROCESS



13. RECOMMENDATIONS

The recommendations resulting from the combination of the results from this project and the Phase 1 project fall into two categories: the use of the combined findings and future work beyond the scope of the two phases to increase the usefulness of the results for the designer and operator.

13.1 Use of the Results From the Phase 1 and 2 Studies

a) From this project, the designer can select those design features which best meet the needs of the mission roles of a new design. This is achieved through use of the models and the understanding of the role of the individual design features in determining performance. This can be done with confidence, since

i) - the results of this study cover virtually the full range of parameters and features currently used on icebreakers; and
ii) - the results are derived directly from full scale performance.

b) The designer, owner or operator can use the results of this study to obtain a true measure of the performance of virtually any type of icebreaking vessel, in an extensive range of environmental conditions and for a wide range of ship operations.

13.2 Further Development of the Methodology

a) The database and analysis established in Design Syntheses 1 & 2 is the most comprehensive to date. It should be extended and updated to incorporate all performance data, including new data as it becomes available. This will allow improved definition of performance in terms of additional features and environmental conditions.

b) The study has resulted in the definition of relationships between design and performance for several performance categories not currently translated into performance models. These performance models should be developed. Some of the performance models developed in this study only contain basic parameters. They should be upgraded.

c) Standard procedures and methodologies should be established for the conduct, measurement, documentation and analysis of full scale ice trials. This should include those performance categories commonly investigated , such as level icebreaking, and performance categories that need to be recognized as important, such as channel breakout.

d) Good environmental data must be collected and documented in full scale tests to enable a valid comparison between different tests.

e) The methodology for correcting full scale level ice performance for environmental conditions should be developed further, to include the results of the most recent and ongoing research, into a standard procedure, that could be adopted by Canadian researchers, designers, owners, and operators.

f) The project has provided the clearest insight to date on those design factors which determine the turning ability in ice of conventional form vessels. This information points logically to the use of captive model tests for further development of turning performance prediction. A model test program is recommended for evaluation of the factors of steering system forces, waterline shape parameters, side slope angle and ice strength. The program would also establish the methodology for turning performance prediction by model test and provide component forces for the development of analytical predictions.

g) The performance of ships in actual ridge and rubble fields depends upon the ram cycle times and penetration distances achieved. Ships with different dimensions, hull forms and powers (or thrusts) will have different performances. The methodologies developed in this study address these factors. They should be combined into a ridge field performance simulation model which is capable of determining the efficiency of different designs.

h) Ice escort is the primary mission for the vessels in the phase 2 study. It is clear that the capabilities of the individual ships enable the mission to be performed in different ways. It is not clear however, which ship features and capabilities enable the mission to be carried out in the most efficient way. Using the methodologies developed in this study, the relationships between performance and ability to carry out the escort mission should be developed and criteria established to enable comparisons between vessel with different capabilities.

i) The ships in the Phase 1 and 2 studies spend considerable time in open water. For many of the ships this involves significant periods in rough water. The ability to maintain speed in these conditions is dependent upon their seakeeping abilities. It is clear from the interviews that the different designs have different seakeeping characteristics, but the differences are not quantifiable. The full scale results do not contain any seakeeping tests. In addition the calm open water resistance of chined and conventional hulled icebreakers is significantly different. As the design of an icebreaker involves tradeoffs between the icebreaking and open water requirements, the relationships between icebreaking design features, seakeeping and open water resistance should be determined and criteria established to determine the tradeoffs.

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